Probing Matter-Antimatter Asymmetry in the Universe using Muons from B Meson Decays at D0

Fermilab Joint Theoretical-Experimental Seminar
19th October 2012

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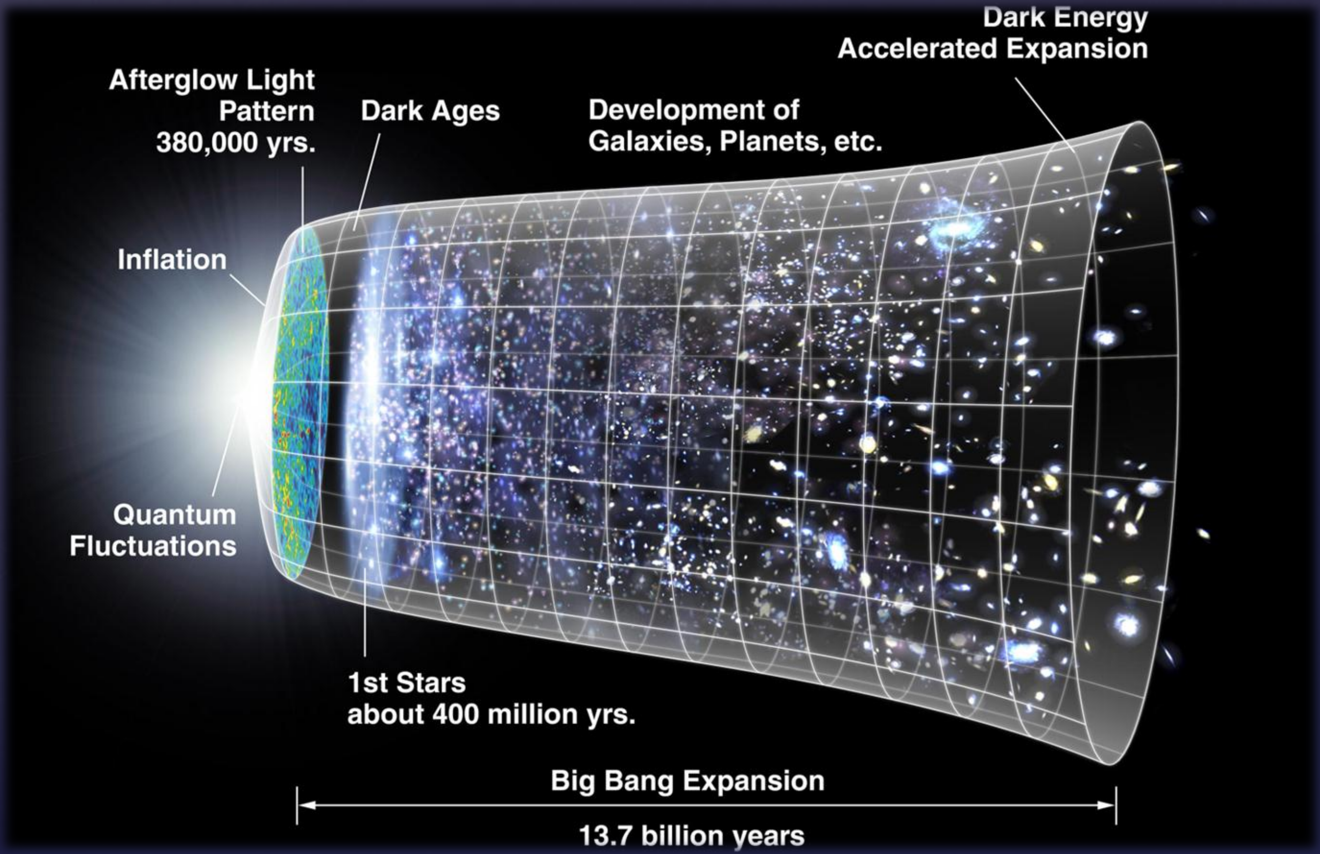
On behalf of the D0 Collaboration

Matter Dominance in the Universe

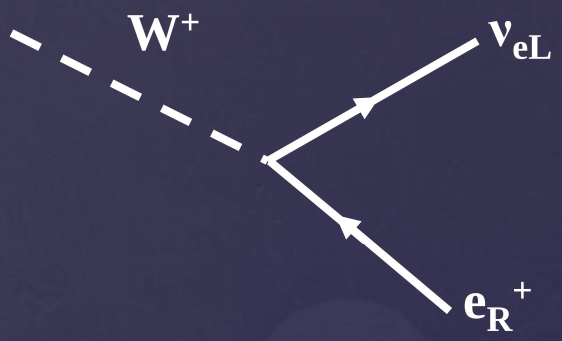
Matter-antimatter symmetric big bang $\xrightarrow[\textit{baryogenesis}]{?}$ Matter dominated Universe



To generate asymmetry, need three conditions (*Sakharov*):

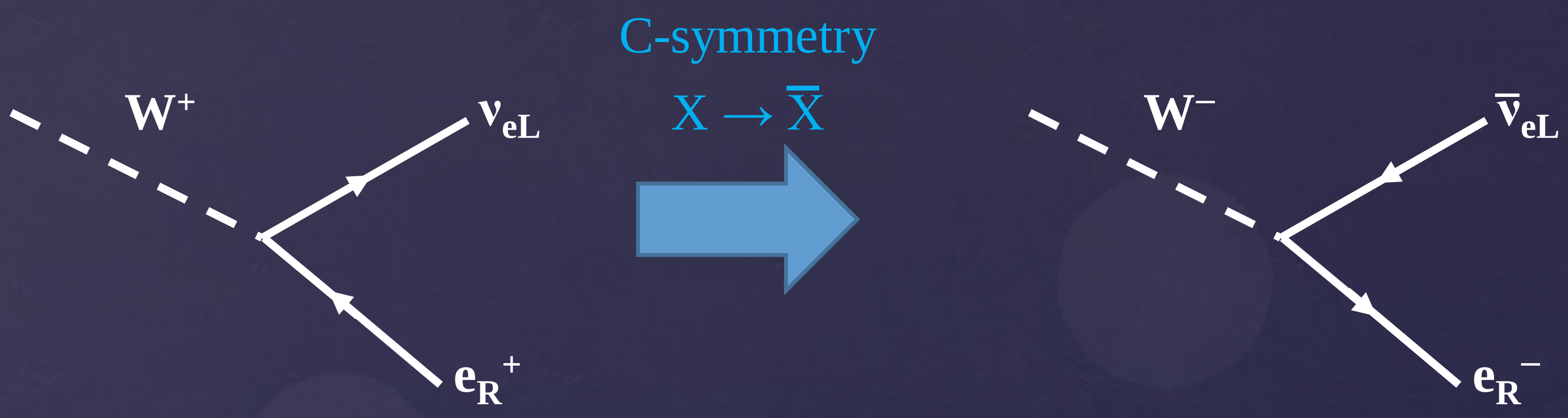
- Baryon number violation
- **C and CP symmetry violation**
- Interactions out of thermal equilibrium

C, P, and CP Symmetries

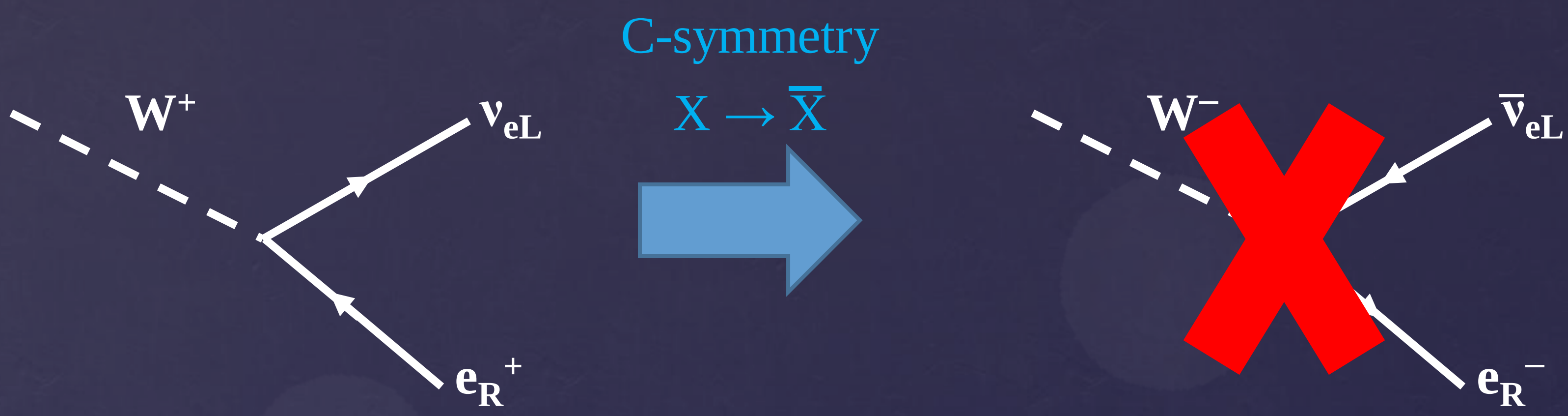


Charged weak interaction **maximally violates** C and P symmetries

C, P, and CP Symmetries



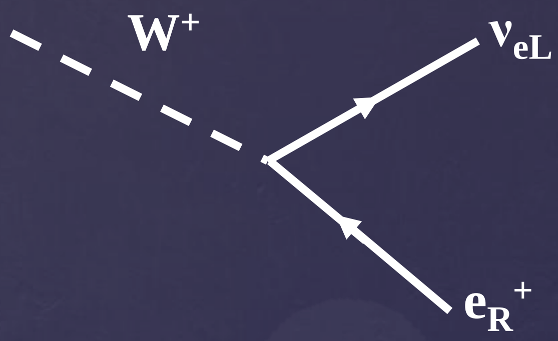
C, P, and CP Symmetries



$W^{\pm}$ bosons only couple to *left-handed* particles and *right-handed* antiparticles

C-violation necessary for baryogenesis, otherwise equal numbers of baryons and antibaryons would be produced

C, P, and CP Symmetries

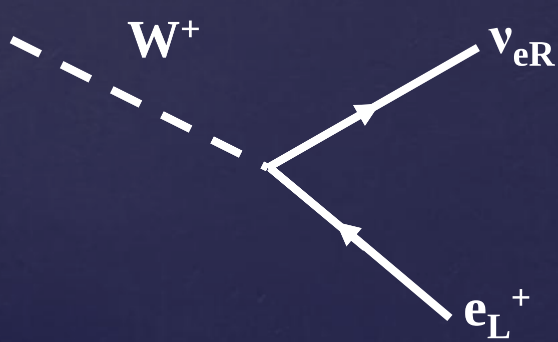


C-symmetry

$X \to \bar{X}$

P-symmetry

$(x,y,z) \to (-x,-y,-z)$



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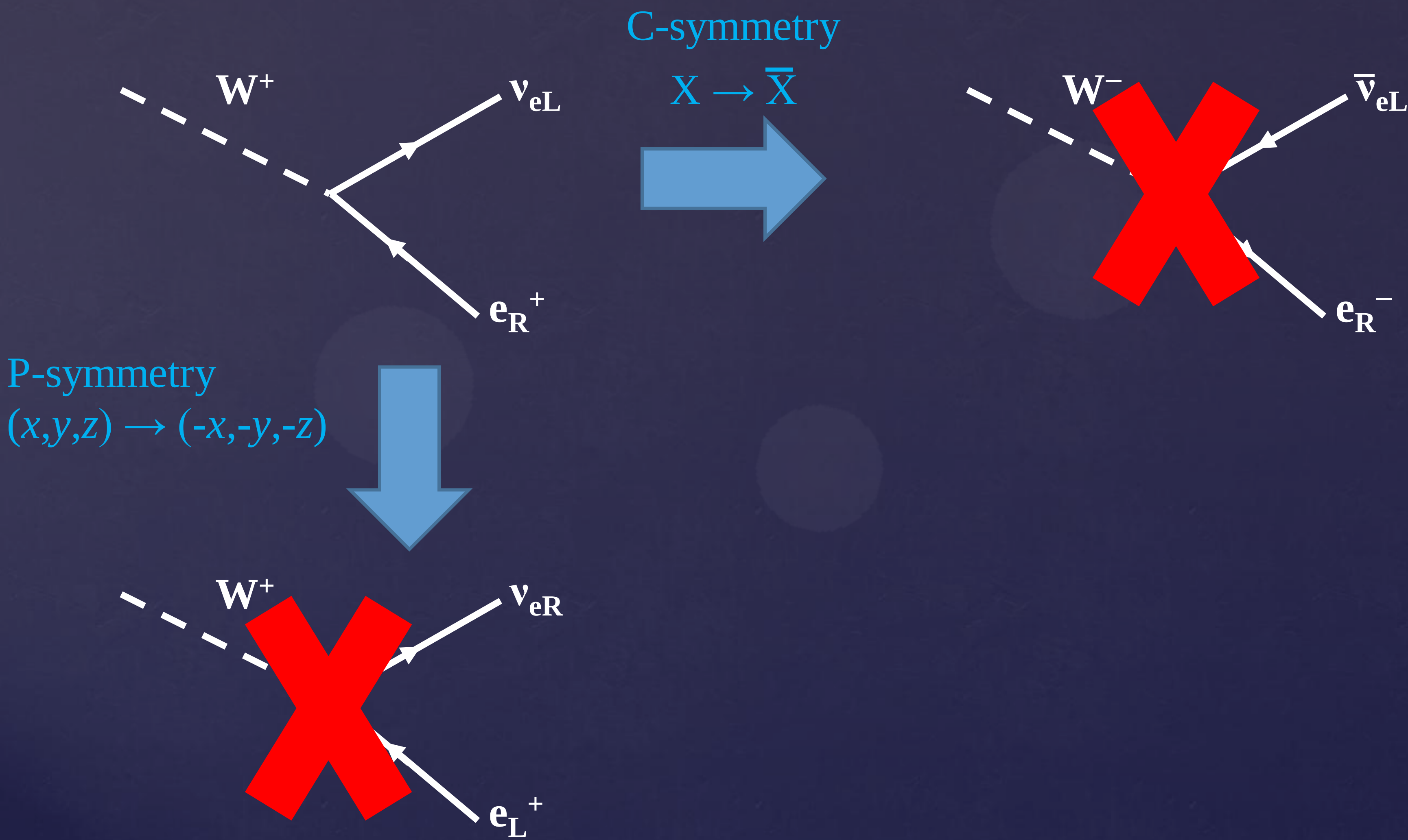

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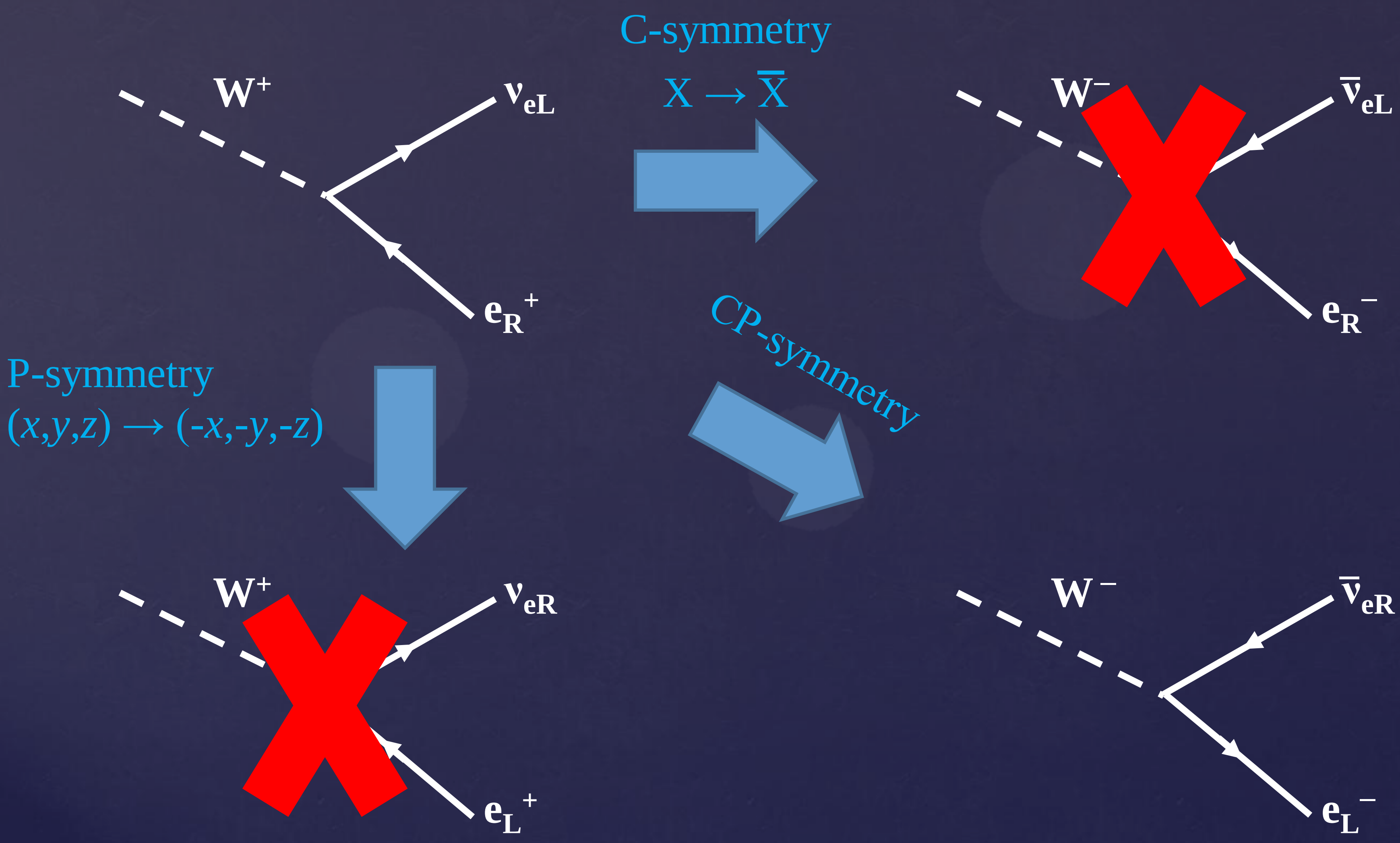

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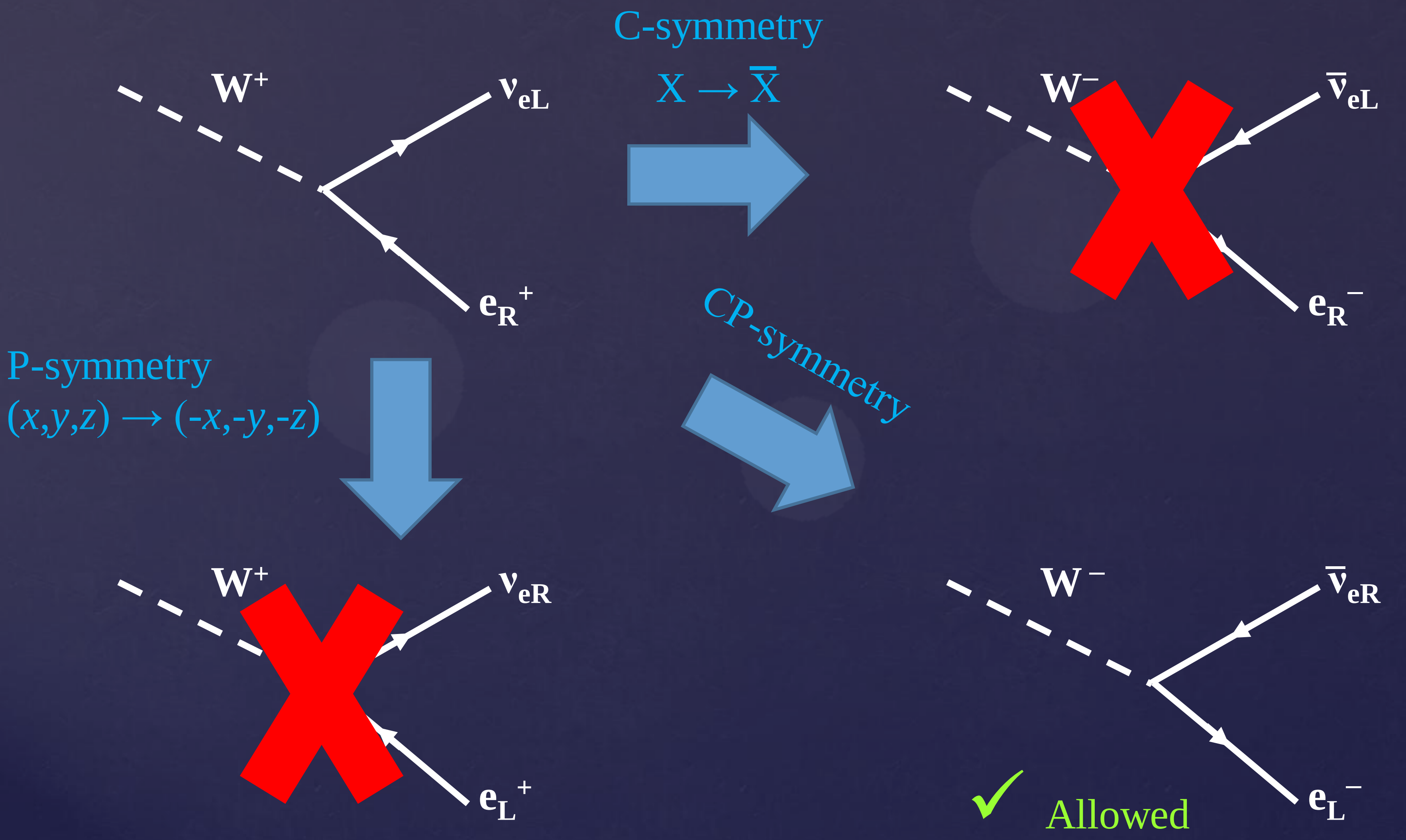

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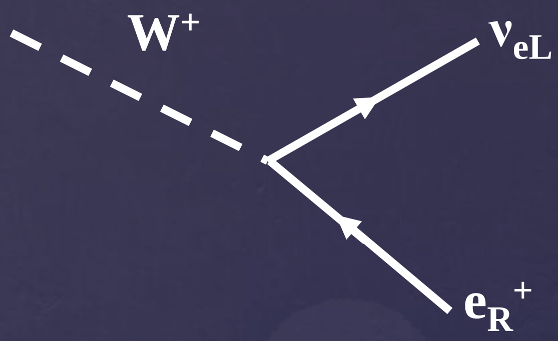
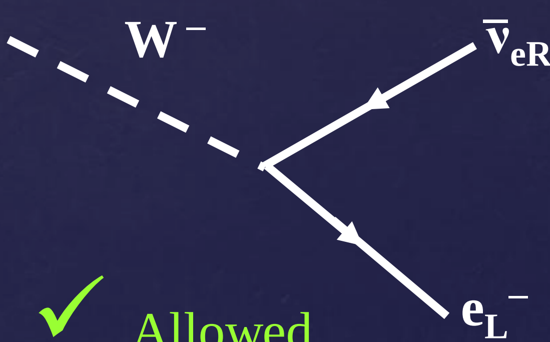
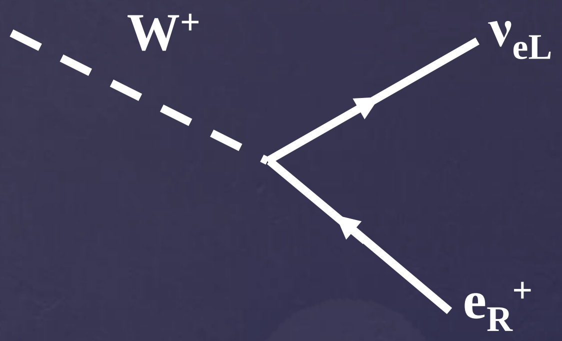


CP violation is a necessary condition of baryogenesis: otherwise equal numbers of left-handed baryons and right-handed antibaryons would be produced.



✓ Allowed

C, P, and CP Symmetries



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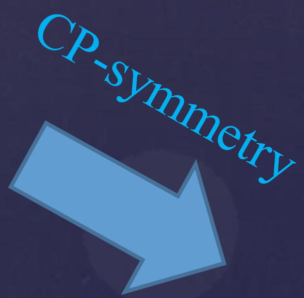
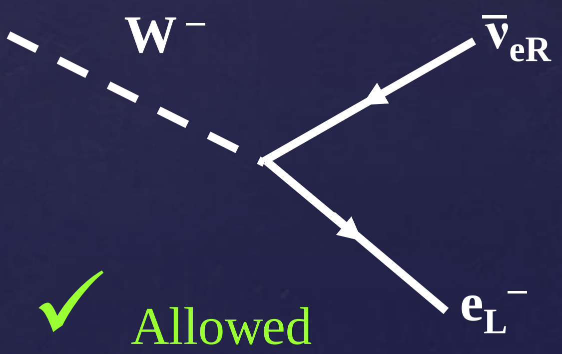


CP violation first observed in neutral kaons (1964):

$\mathbf{\Gamma(K_L^0 \to \pi^- e^+ \bar{\nu}_e) > \Gamma(K_L^0 \to \pi^+ e^- \nu_e)}$

Allows matter and antimatter to be distinguished



CPV in the Standard Model

CKM Quark mixing matrix: 3 mixing angles and one *complex phase* δ

Nonzero complex phase ↔ CP violation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$\boldsymbol{V_{\mathrm{CKM}}}$

$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

CP transformation: $i \rightarrow -i$

Complex matrix elements different for particle and antiparticle interactions

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CPV impossible in 2x2 matrix ⇒ observation of CPV in quark sector motivated three generation model (1973) four years before discovery of b quark at Fermilab (1977)

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$$\begin{array}{c} \\ \end{array}\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \overbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}^{V_{\mathrm{CKM}}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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CPV impossible in 2x2 matrix ⇒ observation of CPV in quark sector motivated three generation model (1973) four years before discovery of b quark at Fermilab (1977)

Level of CPV in the SM **far too small** to account for matter-antimatter asymmetry

Vital to test CKM matrix and search for new sources of CPV

Types of CP Violation

Three categories of CP violation:

1) Direct $\Gamma(A \to f) \neq \Gamma(\bar{A} \to \bar{f})$

Quantified by asymmetries in decay branching ratios, e.g.

$$A_{D^0_+K^\pm} \equiv \frac{\Gamma(B^- \to D^0K^-) - \Gamma(B^+ \to D^0K^+)}{\Gamma(B^- \to D^0K^-) + \Gamma(B^+ \to D^0K^+)} = +0.19 \pm 0.03 \quad (>5\sigma)$$

Types of CP Violation

Three categories of CP violation:

1) **Direct** $\Gamma(A \to f) \neq \Gamma(\bar{A} \to \bar{f})$

2) **In mixing** $\Gamma(A \to \bar{A}) \neq \Gamma(\bar{A} \to A)$

Quantified by asymmetries in mixing of neutral K, D, B mesons, e.g.

$$a^{d}_{sl} \equiv \frac{\Gamma(\bar{B}^0 \to B^0 \to \ell^+ X) - \Gamma(B^0 \to \bar{B}^0 \to \ell^- X)}{\Gamma(\bar{B}^0 \to B^0 \to \ell^+ X) + \Gamma(B^0 \to \bar{B}^0 \to \ell^- X)}$$

Today's topic

Not yet observed in B, D mesons

Types of CP Violation

Three categories of CP violation:

1) **Direct** $\Gamma(A \to f) \neq \Gamma(\bar{A} \to \bar{f})$

2) **In mixing** $\Gamma(A \to \bar{A}) \neq \Gamma(\bar{A} \to A)$

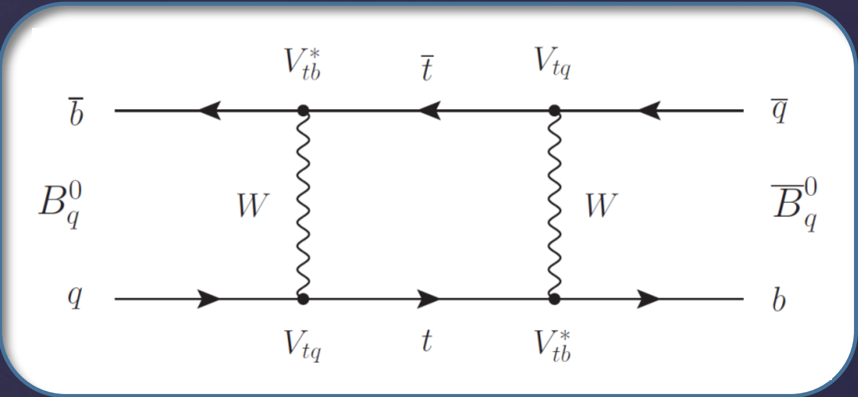
3) **In interference between mixing and decay**

Quantified by asymmetries in decays of neutral mesons, where ***same final state*** is allowed for direct and mixed decays, e.g.

$$A_{\varphi K^0}(t) \equiv \frac{d\Gamma/dt(\bar{B}^0 \to \varphi K^0) - d\Gamma/dt(B^0 \to \varphi K^0)}{d\Gamma/dt(\bar{B}^0 \to \varphi K^0) + d\Gamma/dt(B^0 \to \varphi K^0)}$$

B Meson Oscillations and CPV

Neutral B mesons oscillate into their antiparticles via weak interactions:



Time-evolution governed by Schrödinger equation:

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \underbrace{\left(M^q - \frac{\mathrm{i}}{2}\Gamma^q\right)}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

Heavy (B_{qH}) and light (B_{qL}) mass eigenstates are superpositions of flavor eigenstates…

… Obtained by diagonalising this matrix

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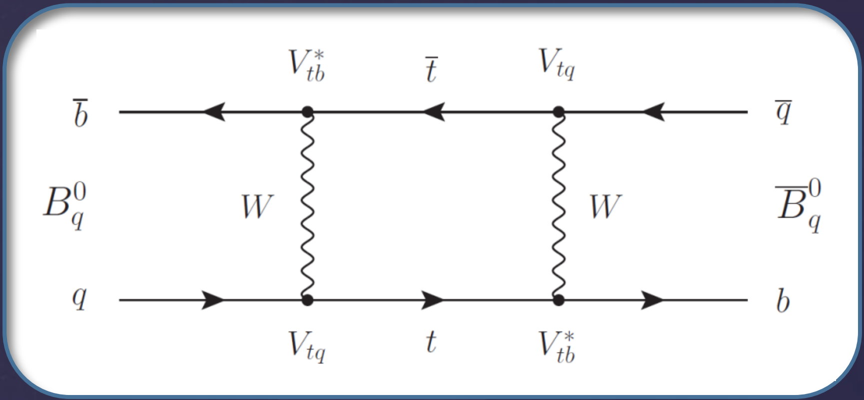

System parameterized by:

Mixing frequency $\Delta M_q = M(B_{qH}) - M(B_{qL})$ $(= 2|M^q_{12}|)$

Lifetime difference $\Delta\Gamma_q = \Gamma(B_{qL}) - \Gamma(B_{qH})$ $(= 2|\Gamma^q_{12}|\cos\varphi_q)$

Complex mixing phase $\varphi_q = \arg(-M^q_{12}/\Gamma^q_{12})$

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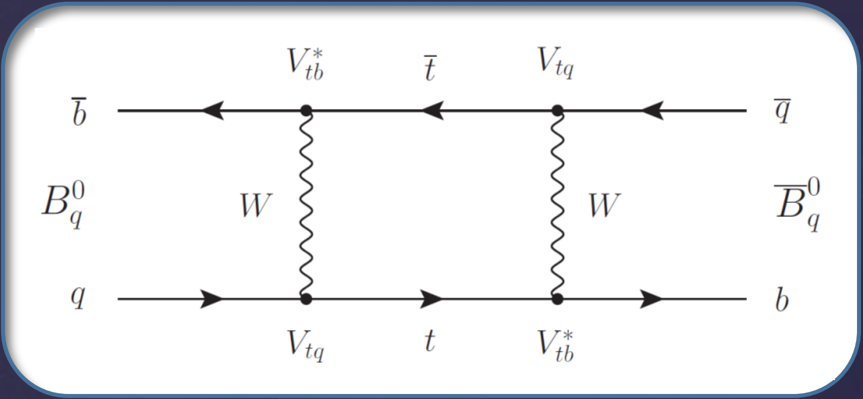

Oscillations very well-established in both B^0 and B_s^0 systems:

$\Delta M_d = 0.507 \pm 0.004\ ps^{-1}$

'slow' mixing: probability of oscillation prior to decay depends strongly on decay time

$\Delta M_s = 17.69 \pm 0.08\ ps^{-1}$

'fast' mixing: experimentally, ~50% oscillation probability ~regardless of decay time

B_s^0 mixing discovered at Tevatron, 2006

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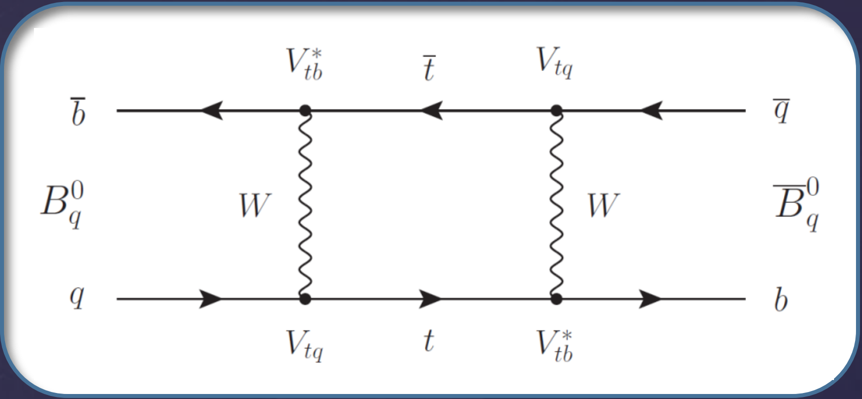

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Complex phase in CKM matrix $\Rightarrow$ **$P[B_{(s)}^0 \rightarrow \bar{B}_{(s)}^0] \overset{?}{\neq} P[\bar{B}_{(s)}^0 \rightarrow B_{(s)}^0]$**

Studies of asymmetries in mixing are a sensitive probe of CPV.

B Meson Oscillations and CPV

Define semileptonic mixing asymmetry:

$$a_{sl}^{q} = \frac{\Delta\Gamma_q}{\Delta M_q} \cdot \tan(\phi_q) = \frac{\Gamma(\bar{B}_q^0 \to B_q^0 \to \ell^+ X) - \Gamma(B_q^0 \to \bar{B}_q^0 \to \ell^- X)}{\Gamma(\bar{B}_q^0 \to B_q^0 \to \ell^+ X) + \Gamma(B_q^0 \to \bar{B}_q^0 \to \ell^- X)}$$

SM values for both B^0 and B^0_s are negligible compared to experimental precision:

$$\left.\begin{array}{l} \mathbf{a^{d}_{sl} = (-0.041 \pm 0.006)\%} \\ \mathbf{a^{s}_{sl} = (-0.0019 \pm 0.0003)\%} \end{array}\right\} \text{SM Predictions}$$

$\mathbf{a^{d}_{sl} = (-0.05 \pm 0.56)\%}$ Current WA value from B Factories

$\mathbf{a^{s}_{sl} = (-0.17 \pm 0.92)\%}$ Previous D0 measurement

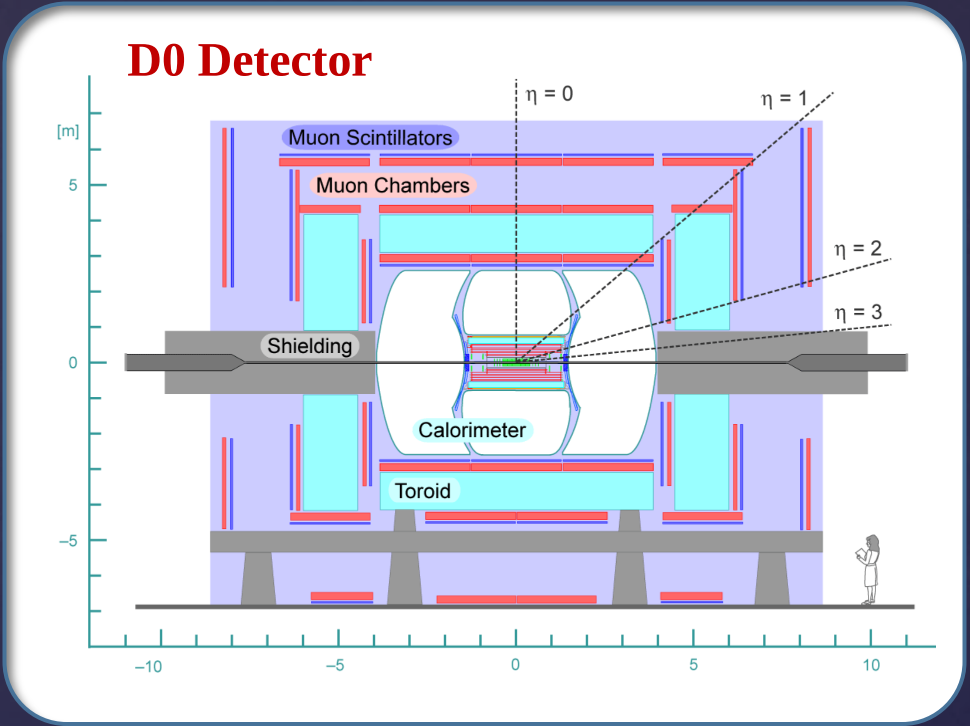
Any significant deviation from zero is hence a signal of new physics.

Muons @ D0

Semileptonic decays provide charged lepton ‘tag’ of B meson flavor at decay time

Experimentally, muons have advantages over electrons at these energies (<20 GeV)

- Easy to identify ⇒ efficient and clean signature for triggers and event selection
- Low ‘fake rate’ : hadronic punchthrough can be suppressed by heavy shielding before muon system
- D0 muon system has wide acceptance (**$|\eta(\mu)| \leq 2$**), with 3 layers of tracking and scintillation detectors



~12-15 interaction lengths before outer muon system

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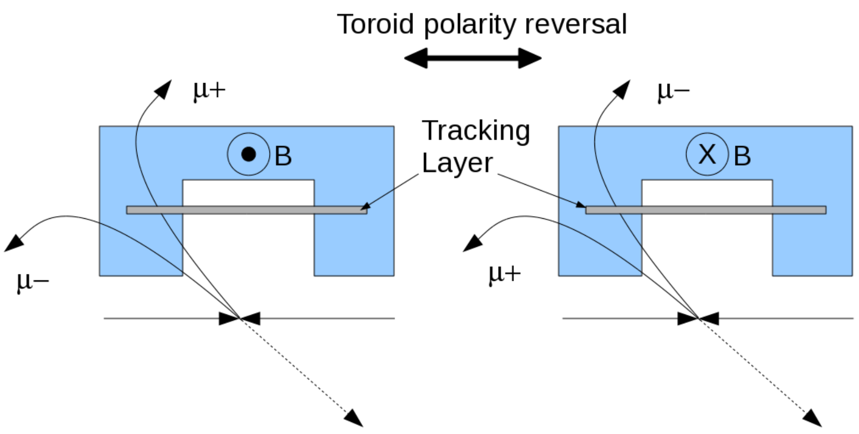

Regular reversal of solenoid (tracking) and toroid (muon) magnets cancels detector asymmetries to first order

Typical tracking detectors have charge asymmetries of 1-3% (range-out, lorentz angle)

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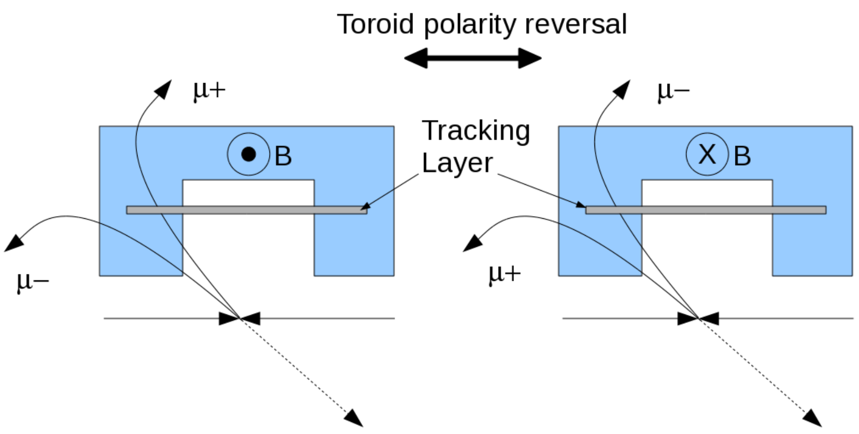


Regular reversal of solenoid (tracking) and toroid (muon) magnets cancels detector asymmetries to first order

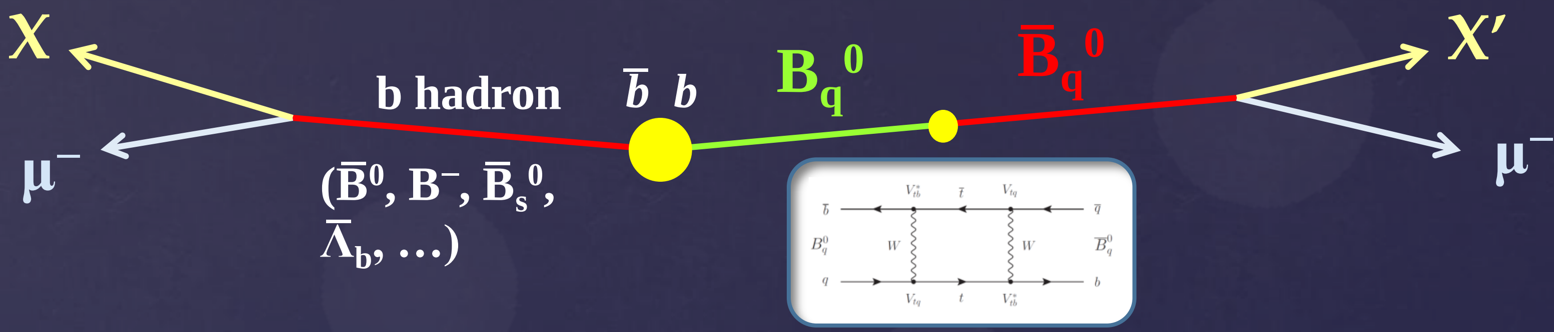
Proton-antiproton collisions @ $\sqrt{s}$ = 1.96 TeV

No production asymmetries: symmetric initial state

Compare LHC: must measure production asymmetries

Same-sign Dimuon Asymmetry

Events with two muons of identical charge have large fraction **(~30%)** from decays of mixed $B_{(s)}^0$ mesons



Measure raw asymmetry $A = \dfrac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$

Relate to 'physical' asymmetry $A^b_{sl} = \dfrac{\Gamma(\bar{b}\rightarrow\mu^+) - \Gamma(b\rightarrow\mu^-)}{\Gamma(\bar{b}\rightarrow\mu^+) + \Gamma(b\rightarrow\mu^-)}$

Contributions from both B^0 and B_s^0 mesons

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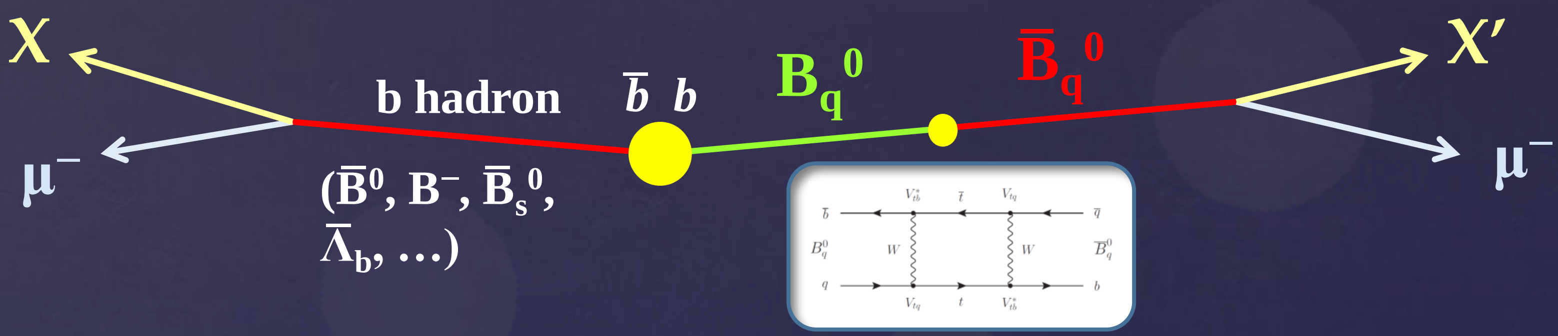

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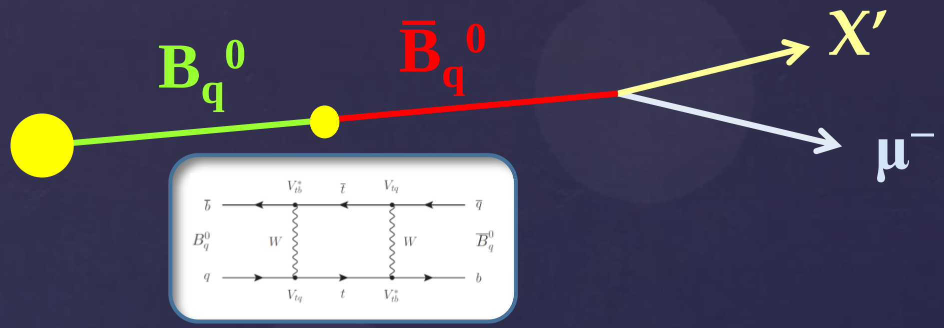
Contributions from both B^0 and B_s^0 mesons

Challenge is understanding contributions from other ~70% of dimuon events

Revisiting Dimuon Asymmetry

First consider single muon asymmetry instead…

Only **~3%** of muons from decays of mixed $B_{(s)}{}^0$ mesons



Measure raw asymmetry $a = \dfrac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)}$

Dominated by backgrounds – *provides essential constraints on these background asymmetries* for the dimuon case.

Revisiting Dimuon Asymmetry

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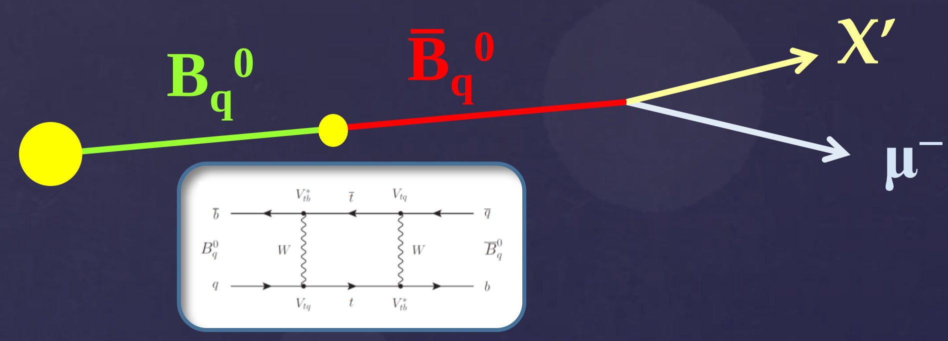
Only **~3%** of muons from decays of mixed $B_{(s)}{}^{0}$ mesons



$$\mathbf{a} = \frac{N(\mu^+) - N(\mu^-)}{N(\mu^+) + N(\mu^-)} = f_{mix} A^b_{sl} + a_{BG}$$

Raw asymmetry (event counting)

Asymmetry from heavy-flavor decays (diluted by $f_{mix} \approx 0.03$)

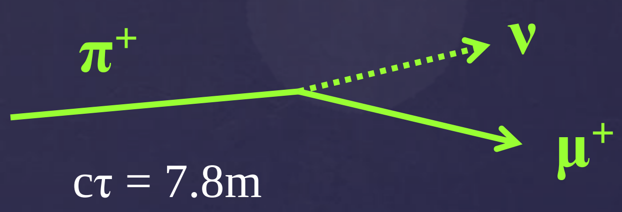
Asymmetries from backgrounds and detector effects…

Revisiting Dimuon Asymmetry

Main background asymmetries: Kaon and pion decay-in-flight to muons (DIF)

~15% of muons

~30% of muons



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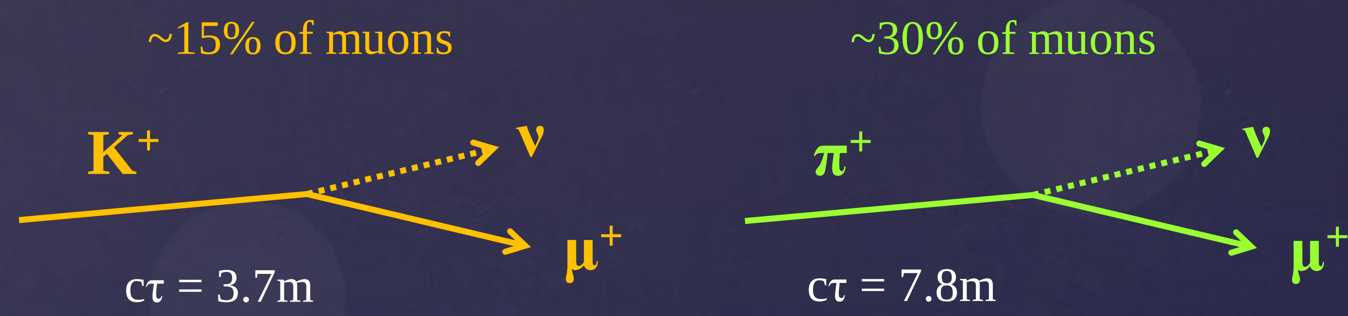


Positive kaons have smaller interaction cross-section than negative kaons in matter

K^+ more likely to survive to decay into muons

$\mathbf{N(K^+ \rightarrow \mu^+) > N(K^- \rightarrow \mu^-)}$

$K^- N \rightarrow Y\pi$

$K^+ N \rightarrow$

@ $p(K)$ = 1 GeV
$\sigma(K^- d) \approx 80mb$
$\sigma(K^+ d) \approx 33mb$

Revisiting Dimuon Asymmetry

In single muon case, expect $\mathbf{a \approx a_{BG}}$

if background asymmetries are determined correctly

fraction *Charge asymmetry*

$$\mathbf{a_{BG} = \underbrace{f_K a_K}_{\text{Kaon DIF and punch-through}} + \underbrace{f_\pi a_\pi}_{\text{Pion DIF and punch-through}} + \underbrace{f_p a_p}_{\text{...proton punch-through}} + (1 - f_K - f_\pi - f_p)\delta}$$

Kaon DIF and punch-through

Pion DIF and punch-through

…proton punch-through

Residual muon reconstruction asymmetries

Asymmetries from backgrounds and detector effects:

- Three fractions
- Four asymmetries

Each computed independently in bins of $p_T(\mu)$, $|\eta(\mu)|$

Use independent and separate channels

Revisiting Dimuon Asymmetry

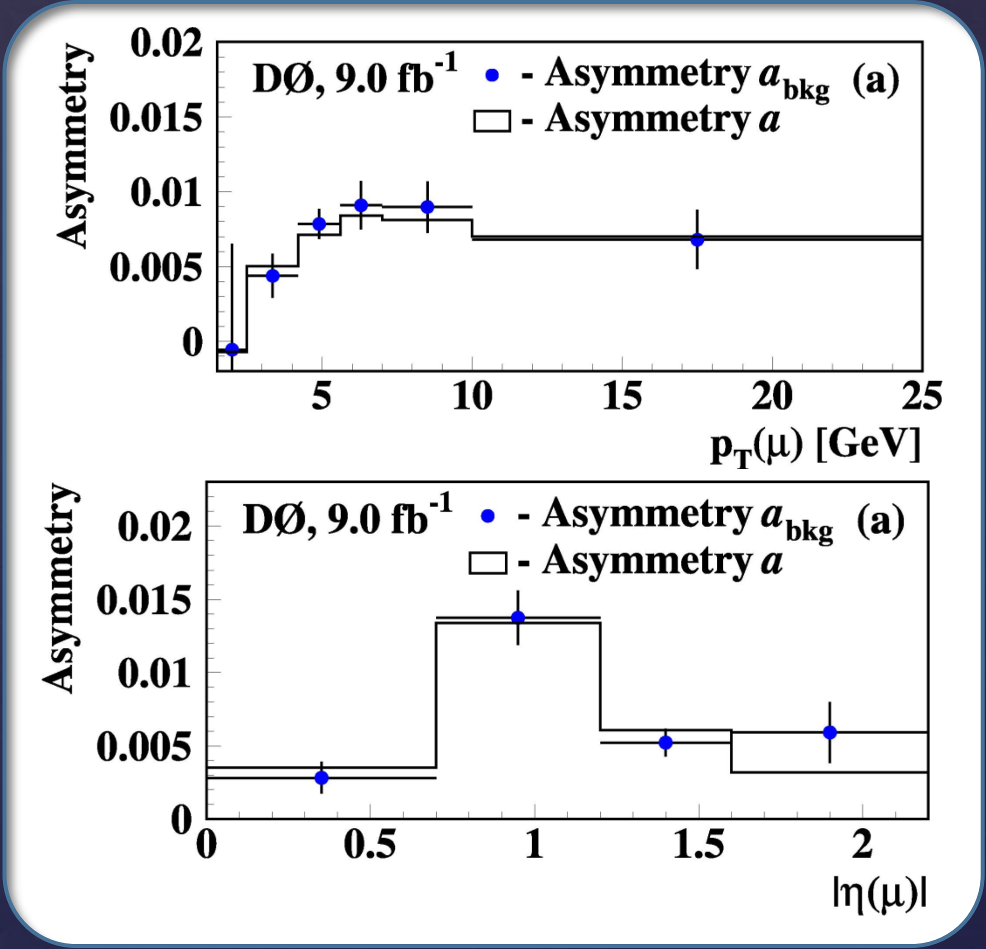
Observed single muon asymmetry agrees with expectations from

- Hadronic decay in flight
- Punchthrough
- Residual muon reconstruction asymmetry

Agreement versus pT(μ) and |η(μ)|

Compelling closure test demonstrating excellent understanding of background asymmetries

>50% of sample is from heavy flavor (non-oscillated) decays, and no indication of anomalous asymmetry



Revisiting Dimuon Asymmetry

Now require second, ***same-charge muon*** in event...

$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

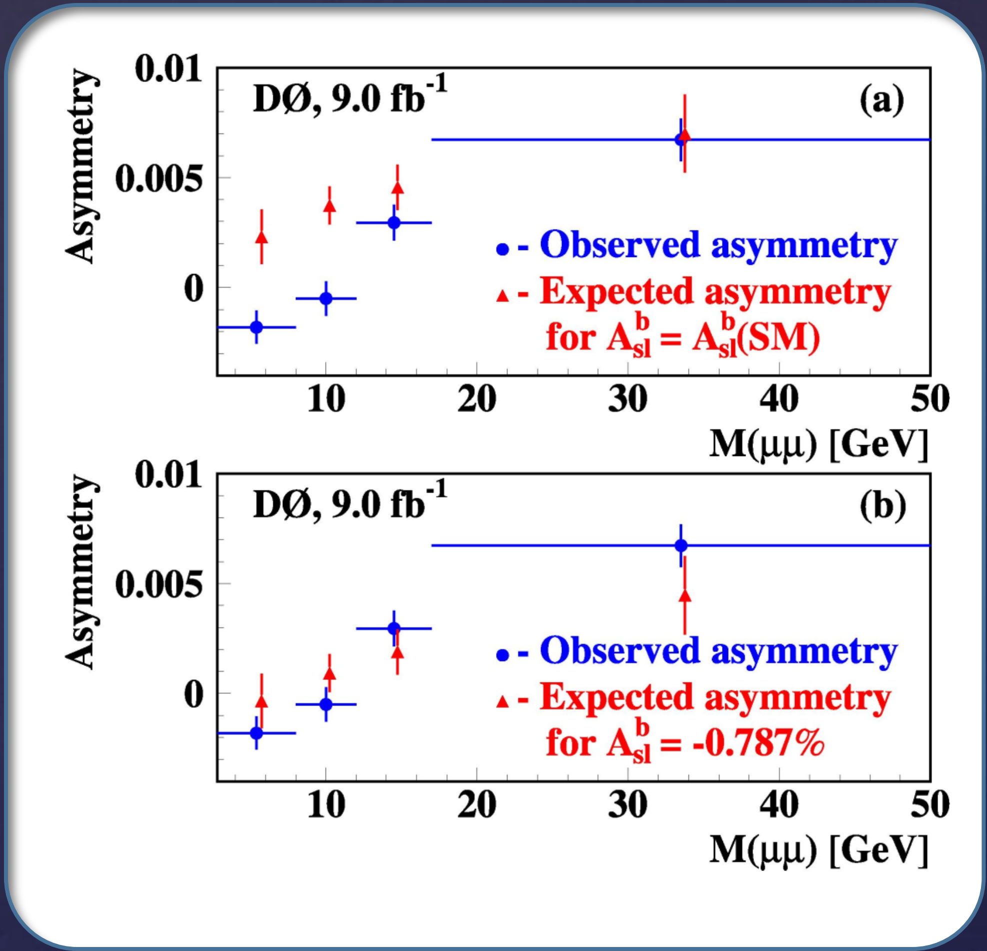
Observed asymmetry significantly different from expected **background asymmetry**,

$$\mathbf{A - A_{BG} = (-0.246 \pm 0.052 \pm 0.021)\ \%}$$

SM: $(-0.009 \pm 0.002)\%$

4.2σ from standard model prediction.

Model-independent.



Revisiting Dimuon Asymmetry

Interpretation

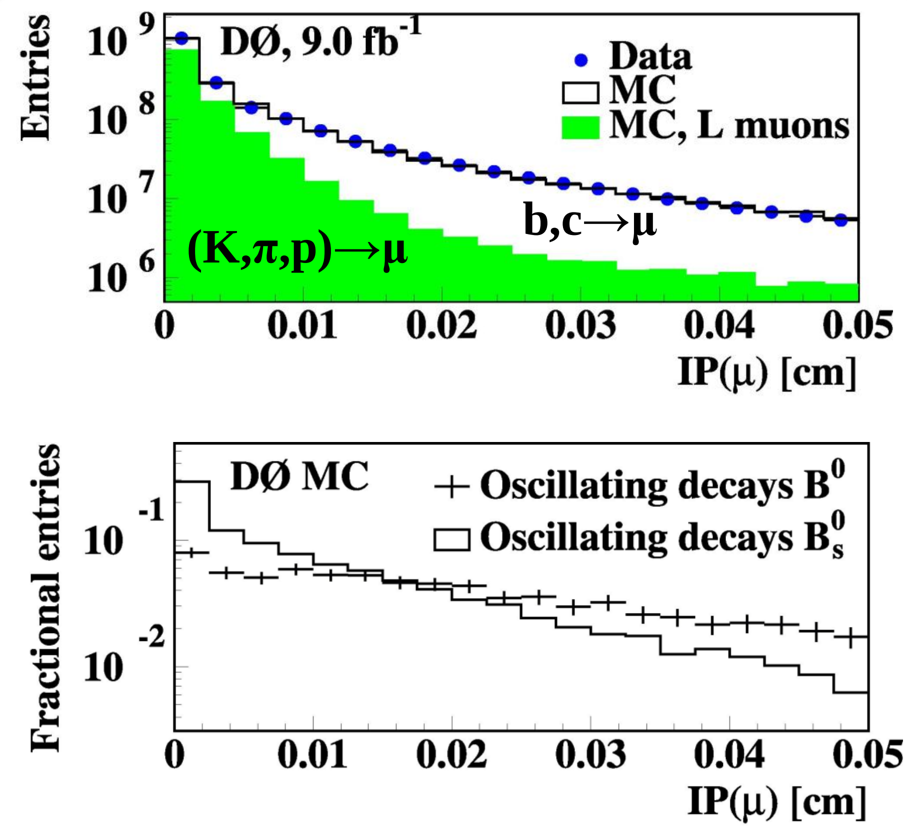
~30% of dimuon candidates in sample include one muon from **semileptonic decay of neutral B meson after oscillation**.

Enhanced oscillated meson fraction, and significant asymmetry, implies that the origin is **CPV in B mixing**.

$A^{b}_{sl} = (-0.787 \pm 0.172 \pm 0.093)\%$

3.9σ from SM prediction

(uncertainty on oscillated B fraction lowers significance slightly)



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Interpretation

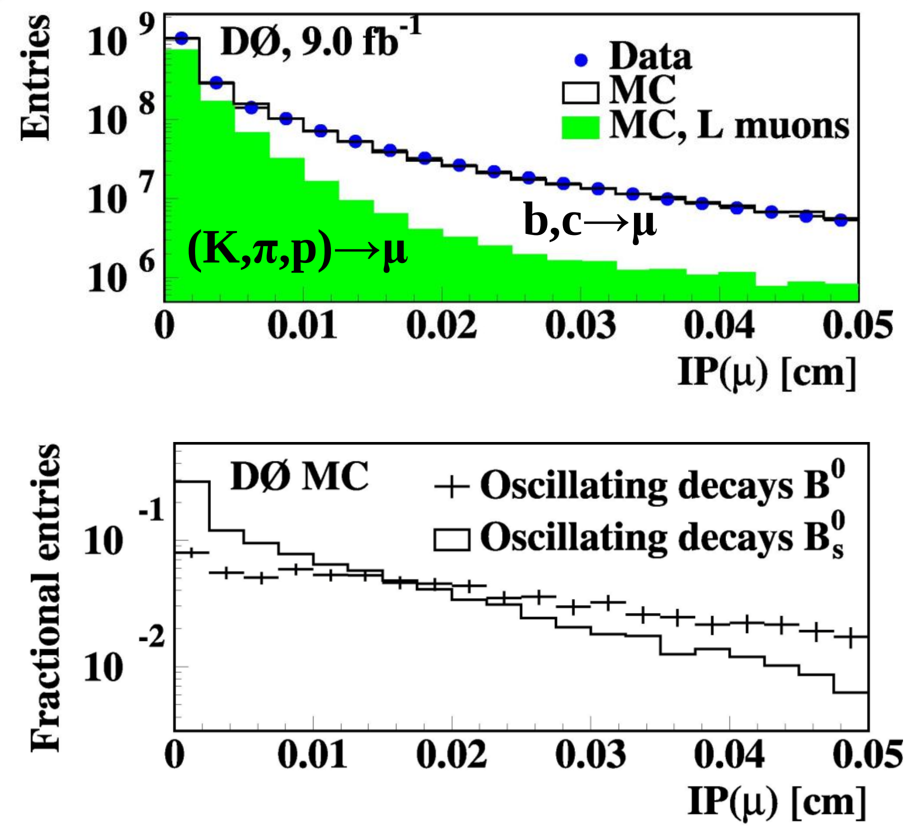
~30% of dimuon candidates in sample include one muon from **semileptonic decay of neutral B meson after oscillation**.

Enhanced oscillated meson fraction, and significant asymmetry, implies that the origin is **CPV in B mixing**.

$A^b_{sl} = (-0.787 \pm 0.172 \pm 0.093)\%$

3.9σ from SM prediction

(uncertainty on oscillated B fraction lowers significance slightly)



Heavy flavor fraction, and oscillated B^0/B_s^0 fractions, are strong functions of impact parameter (IP)

Revisiting Dimuon Asymmetry

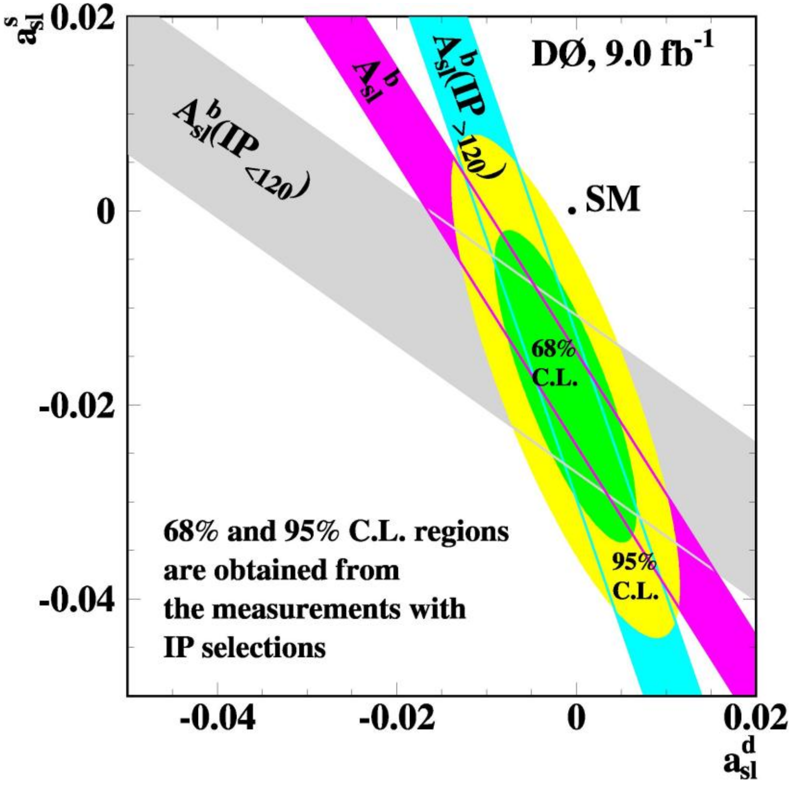
In this interpretation, dimuon asymmetry can include contributions from both B^0 and B_s^0 mesons:

$$A^b_{sl} = C_d\, a^d_{sl} + C_s\, a^s_{sl}$$

Divide sample according to IP, to generate overlapping constraints and allow separate determination of a^d_{sl}, a^s_{sl}

$$a^d_{sl} = (-0.12 \pm 0.52)\%$$

$$a^s_{sl} = (-1.81 \pm 1.06)\%$$



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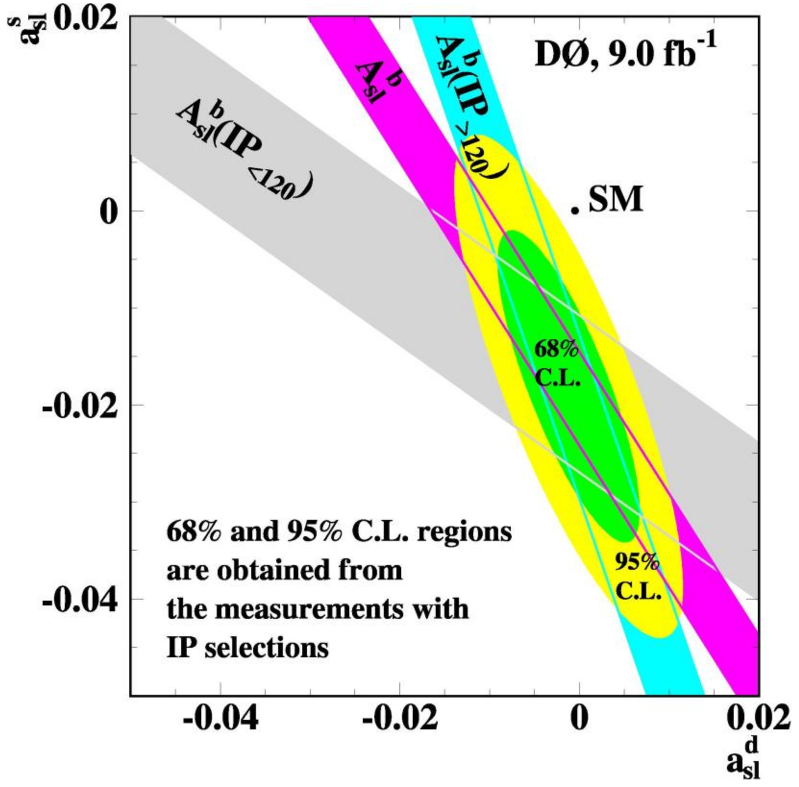


Need further measurements of specific asymmetries in B^0 and B_s^0 meson mixing and decay

Direct Measurements of a^q_{sl}

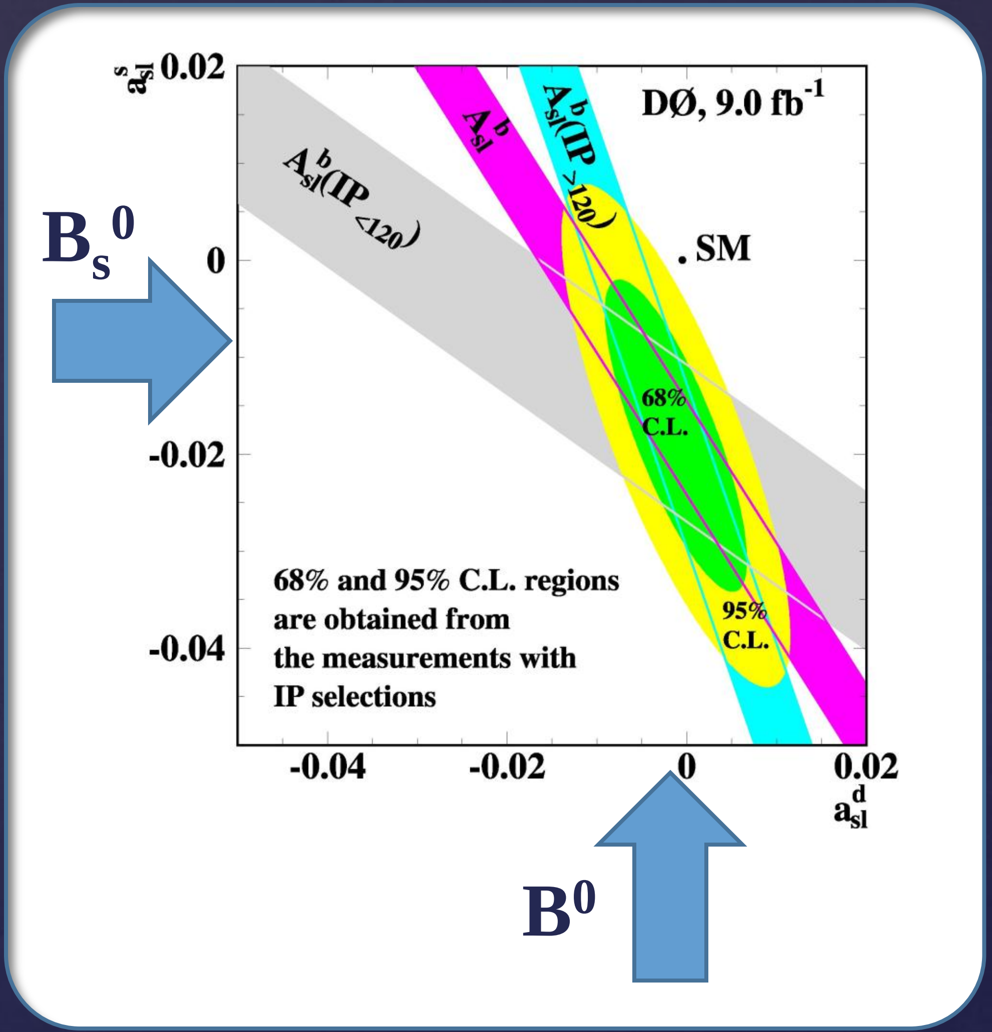
Reconstruct specific decay channels of $B_{(s)}^0$ mesons

Use high statistics samples of semileptonic $\mu D_{(s)}^{(*)\pm}$ decays

Enables simplified extraction of background asymmetries

No ‘flavor-tagging’ at production – instead rely on existing understanding of oscillation parameters

Aim to over-constrain the (a^d_{sl}, a^s_{sl}) plane



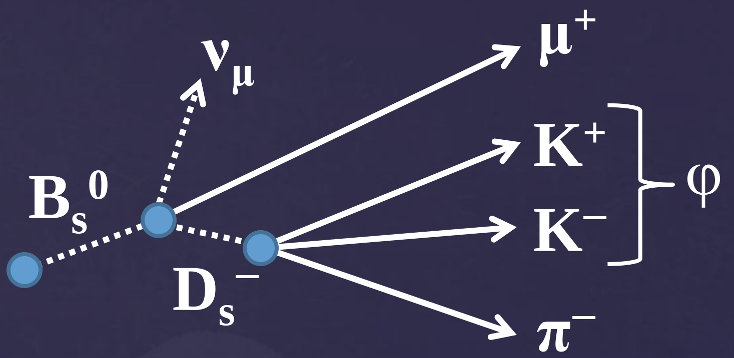
Decays

One decay channel for B_s^0:

$B_s^0 \to \mu^+ \nu D_s^- X$

$D_s^- \to \varphi\pi^-$

$\varphi \to K^+K^-$



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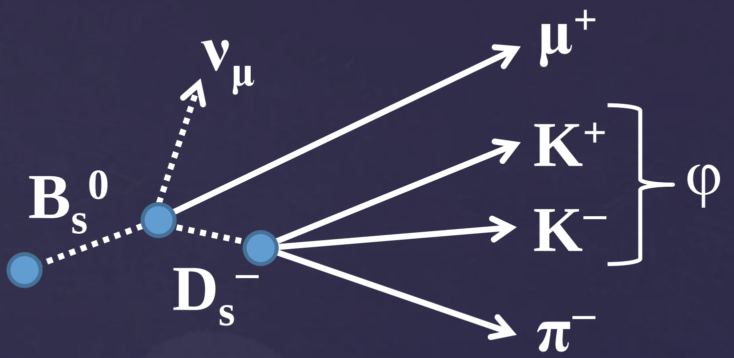
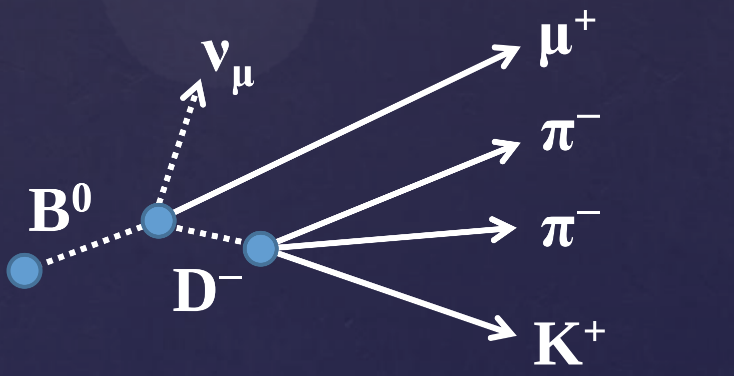


Two decay channels for B^0:

1) $B^0 \to \mu^+ \nu D^- X$

$D^- \to K^+\pi^-\pi^-$



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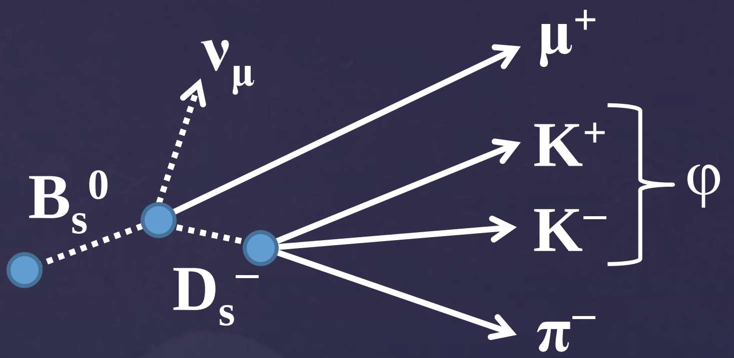

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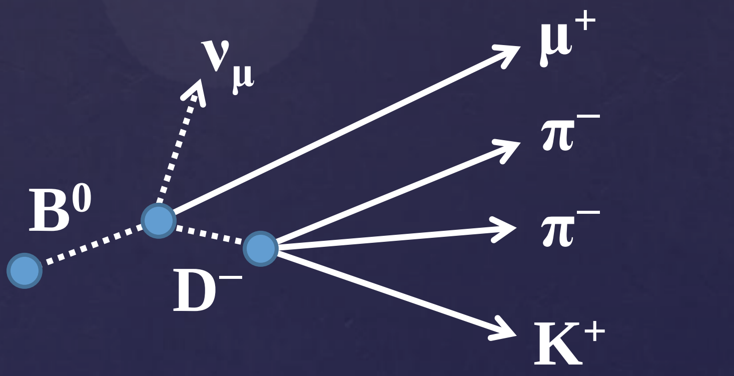
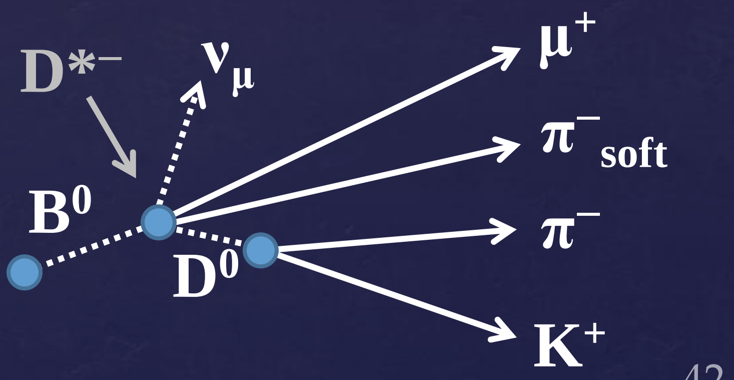


2) $B^0 \rightarrow \mu^+ \nu D^{*-} X$

$D^{*-} \rightarrow D^0\pi^-$

$D^0 \rightarrow K^+\pi^-$



Analysis Overview

For each channel…

Raw asymmetry is extracted by counting $\mu D_{(s)}^{(*)\pm}$ signal yields:

$$A = \frac{N_{\mu^+ D_{(s)}^{(*)-}} - N_{\mu^- D_{(s)}^{(*)+}}}{N_{\mu^+ D_{(s)}^{(*)-}} + N_{\mu^- D_{(s)}^{(*)+}}} \equiv \frac{N_{\text{diff}}}{N_{\text{sum}}}$$

This is related to the semileptonic mixing asymmetry:

$$a_{\text{sl}}^{q} = \frac{A - A_{\text{BG}}}{F_{B_{(s)}^0}^{\text{osc}}}$$

A_{BG}: detector-related asymmetries (e.g. positive kaons have higher detection efficiency).

$\Rightarrow$

$(A - A_{BG})$ is the background corrected physical asymmetry – model independent, ≈ 0 in the SM.

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This is related to the semileptonic mixing asymmetry:

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$F^{osc}_{B^0(s)}$: fraction of reconstructed $\mu D_{(s)}$ decays from oscillated $B^0_{(s)}$ mesons.

$\Rightarrow$

Assume that all other sources of $\mu D_{(s)}$ candidates are charge symmetric (e.g. direct $B^0_{(s)}$ decay, prompt D meson production…)

Analysis Overview

For each channel…

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This is related to the semileptonic mixing asymmetry:

$$a_{\mathrm{sl}}^{q} = \frac{A - A_{\mathrm{BG}}}{F_{B_{(s)}^{0}}^{\mathrm{osc}}}$$

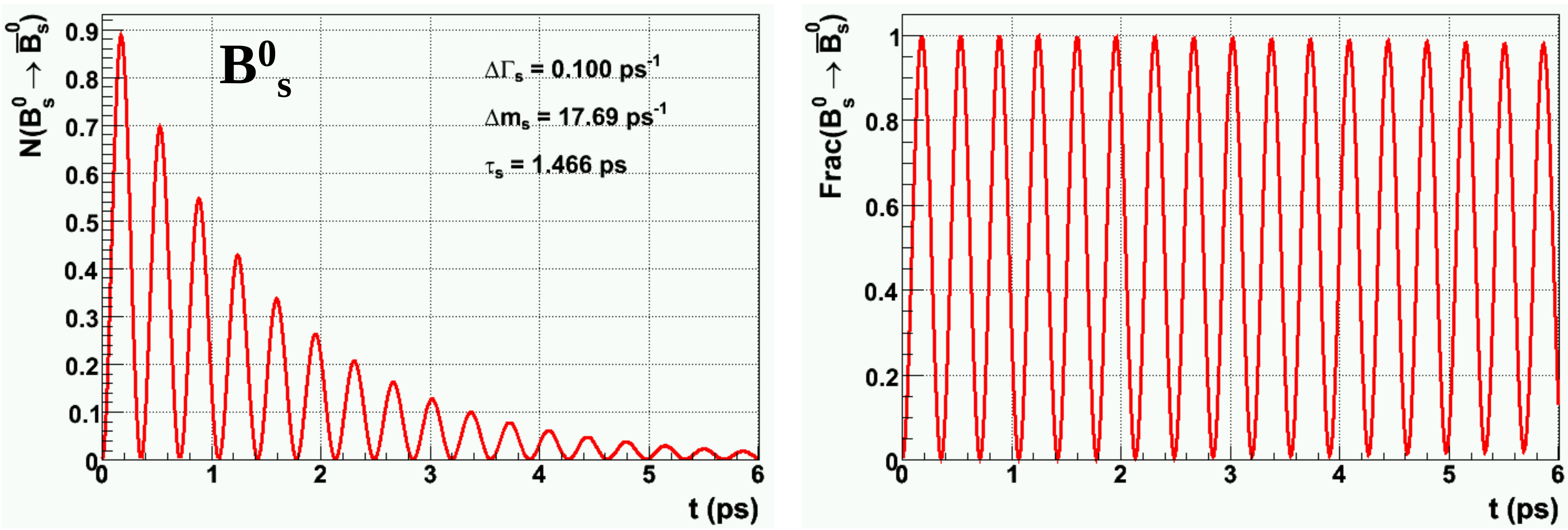
1) Measure **A** by fitting mass distributions for sum and difference;
2) Measure $\mathbf{A_{BG}}$ using data-driven methods from other channels;
3) Determine $\mathbf{F^{osc}_{B^0(s)}}$ using simulation

…then combine inputs to extract a^q_{sl}.

Time Dependence

Meson-antimeson oscillation is a time-dependent process

$\Rightarrow$ non-zero a^q_{sl} manifests as **decay time-dependent asymmetry**



B^0_s mesons: 'fast' oscillation ($\tau_s \Delta m_s$ >> 1)

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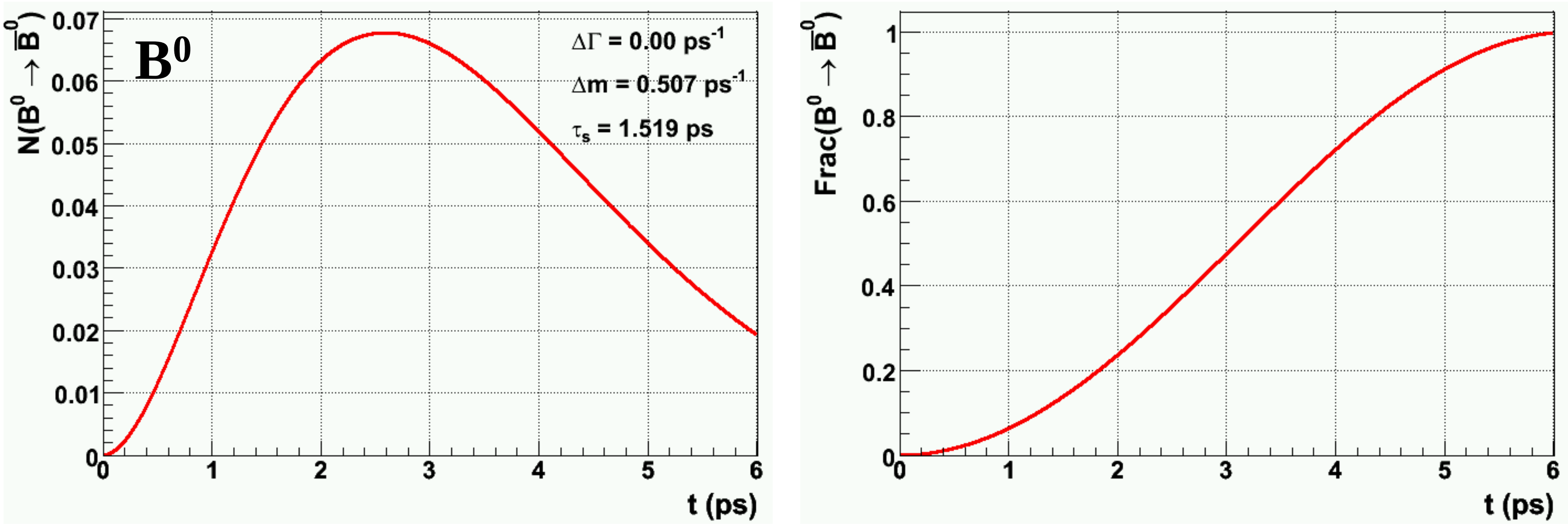

B^0 mesons: 'slow' oscillation ($\tau\Delta m \approx 1$)

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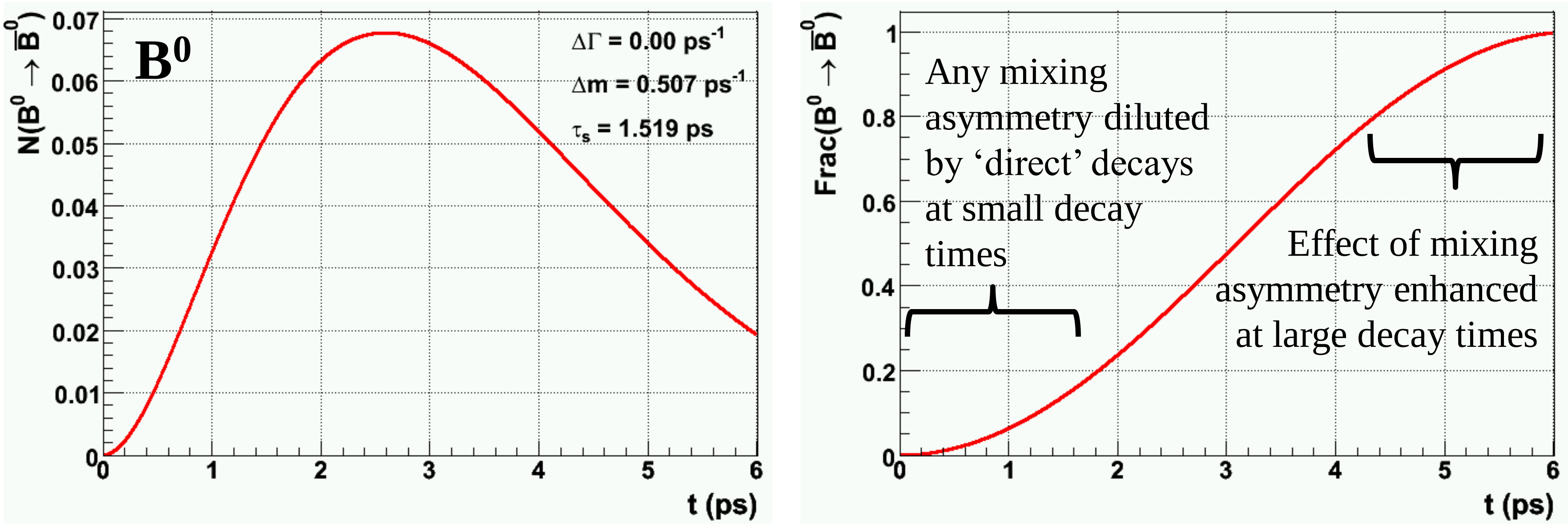


B^0 mesons: 'slow' oscillation ($\tau\Delta m \approx 1$)

~~Time~~ VPDL Dependence

Experimentally, we measure the *decay length* in the transverse plane, L_{xy}:

$$ct = L_{xy}(B)\,\frac{cM(B)}{p_T(B)}$$

In semileptonic decays, the neutrino is undetected: we cannot measure $p_T(B)$, only $p_T(\mu D)$: use *visible proper decay length* (VPDL).

$$VPDL(B) = L_{xy}(B)\,\frac{cM(B)}{p_T(\mu D)}$$

Limitations:

1) Finite resolution on L_{xy}
2) Unknown missing momentum from neutrino

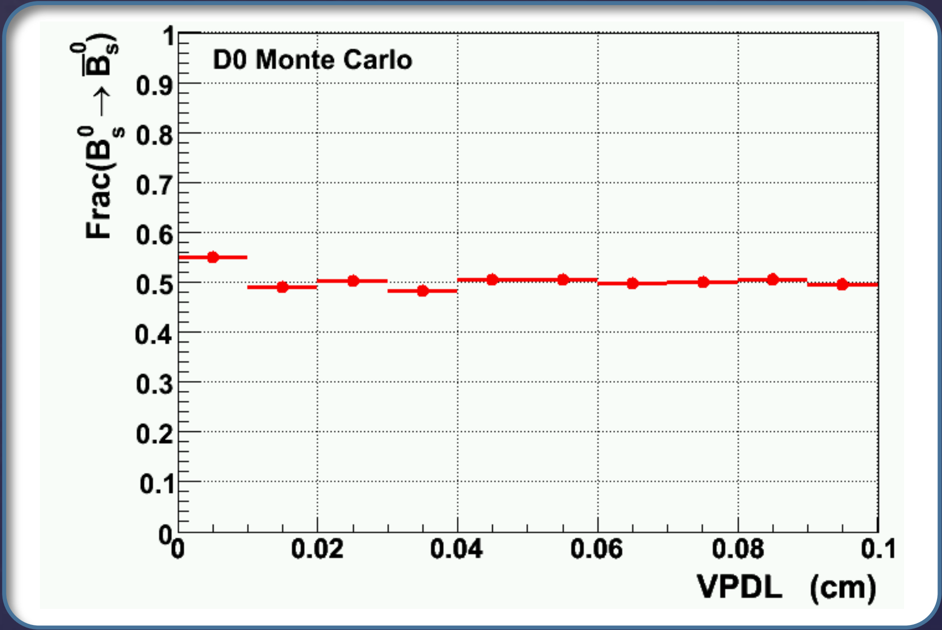
$\Rightarrow$ Reduced sensitivity to fast oscillations
Quantify using Monte Carlo simulations

~~Time~~ VPDL Dependence

B^0_s mesons:

Oscillations washed out in VPDL – little to be gained from time-dependent analysis.

i.e. for any measured decay time, probability of oscillation is ~50%



⇒ Perform single time-integrated measurement and benefit from reduced systematic uncertainties.

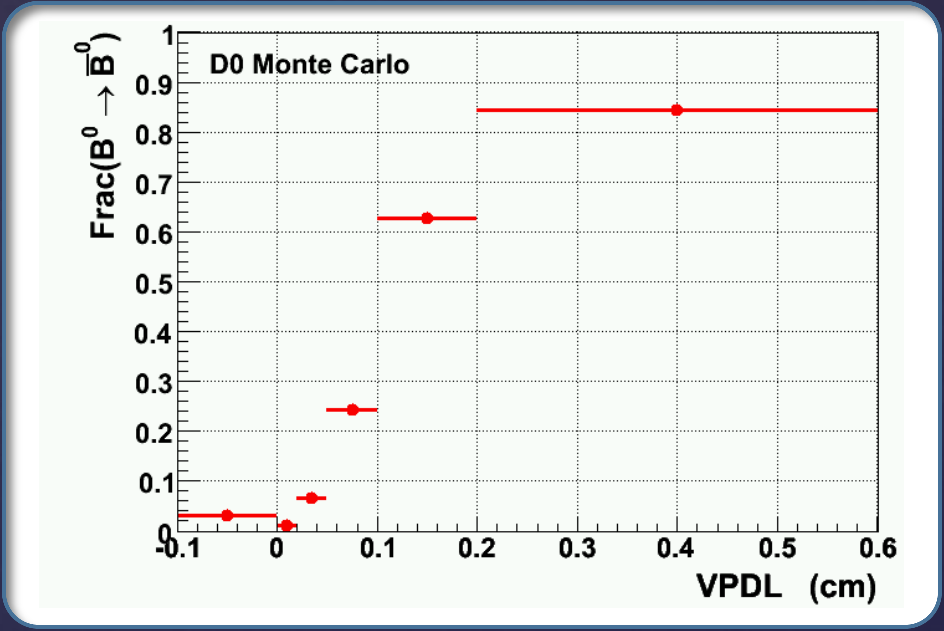
~~Time~~ VPDL Dependence

B^0 mesons:

Oscillation still clear versus VPDL

Small VPDL: sample dominated by direct decays of non-oscillated B^0
$\rightarrow$ little sensitivity to a^d_{sl}

Large VPDL: sample dominated by decays of oscillated B^0
$\rightarrow$ good sensitivity to a^d_{sl}



$\Rightarrow$ **Divide sample into six VPDL regions and measure a^d_{sl} separately in each.**

~~Time~~ VPDL Dependence

B^0 mesons:

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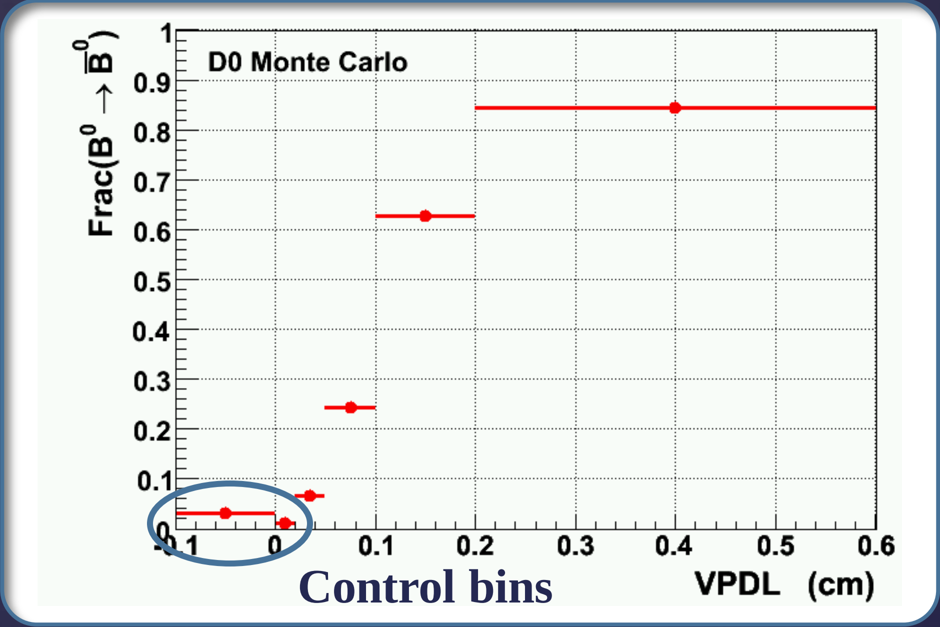

⇒ Divide sample into six VPDL regions and measure a^d_{sl} separately in each.

⇒ First 2 bins are control sample: expect $(A - A_{BG}) \approx 0$

Event Selection

Channels use **common selections** where possible:

- Single and dimuon **triggers**
- High quality **track** in muon system, associated with **central track**

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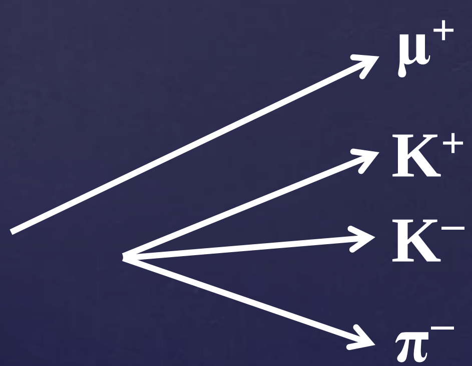
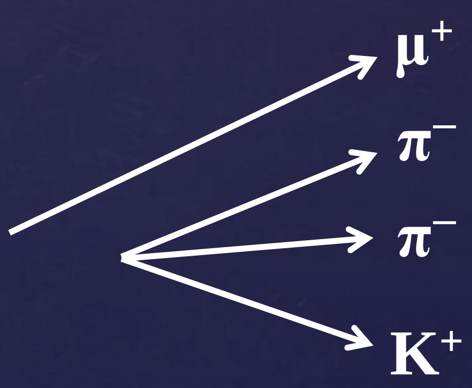
- **3 additional tracks** with total charge q(ttt) = −q(μ), with loose vertex requirements





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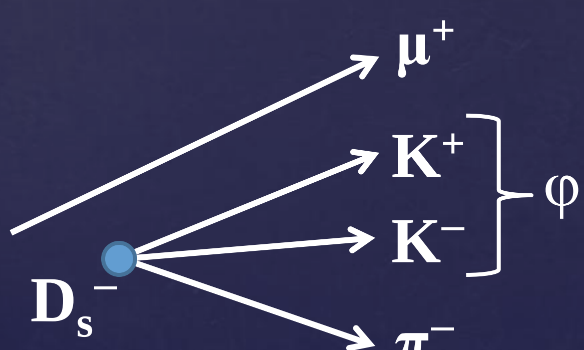

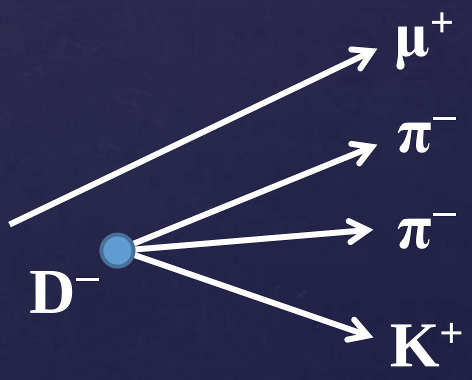

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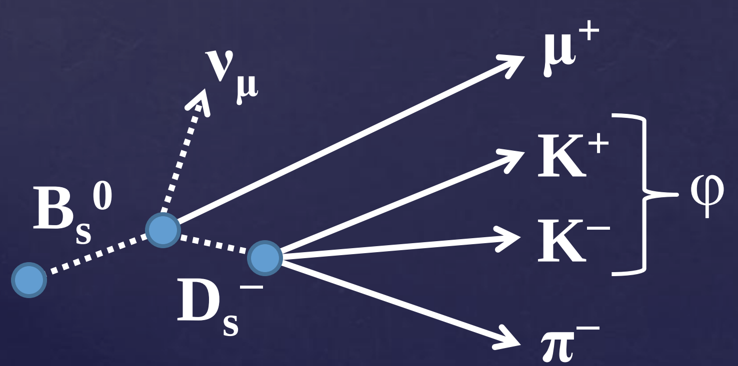
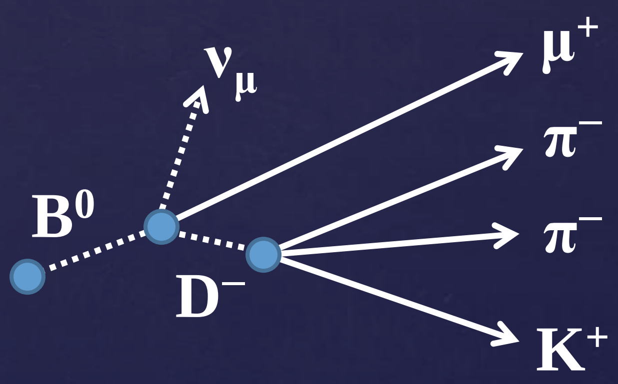
- Trajectories and invariant mass consistent with D meson decay
- Muon and D meson trajectories and mass consistent with semileptonic B meson decay



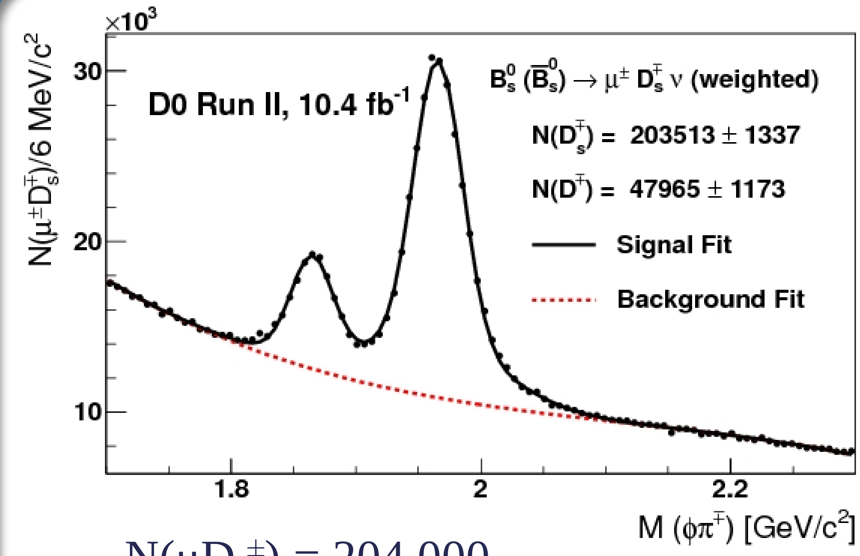


Event Selection

B_s^0 Channel

Final selections use multivariate discriminants

Final cut on multivariate discriminant chosen to maximize signal significance $S/\sqrt{(S+B)}$



$N(\mu D_s^{\pm}) = 204,000$

Event Selection

B_s^0 Channel

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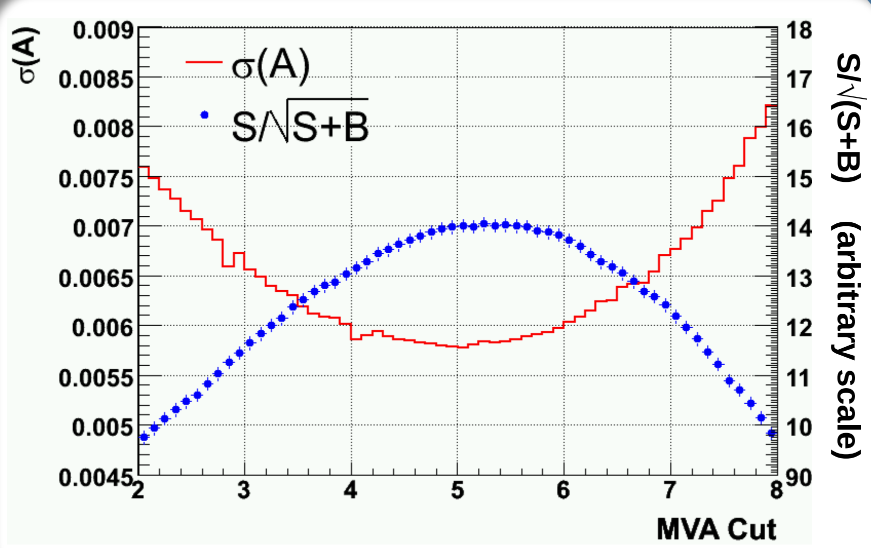
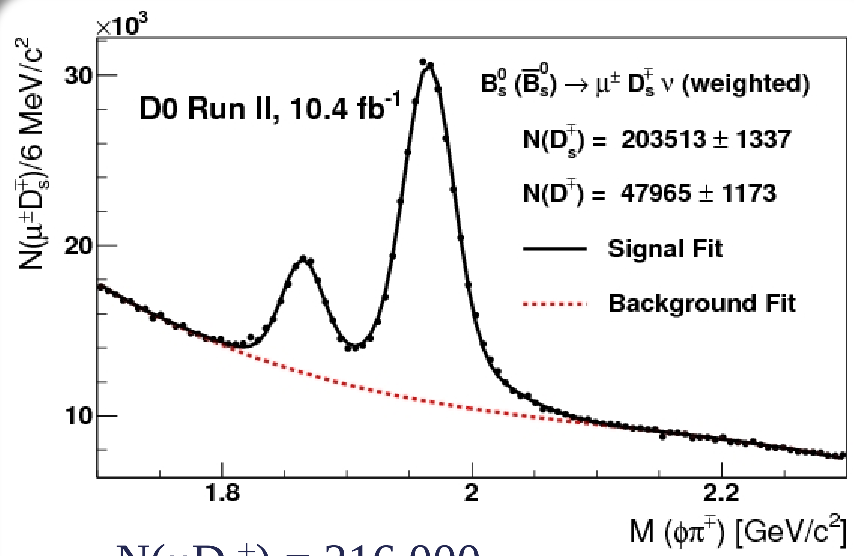




$N(\mu D_s^\pm) = 216{,}000$

Charge-randomised ensemble tests confirm that $S/\sqrt{(S+B)}$ is the proper metric for optimizing performance.

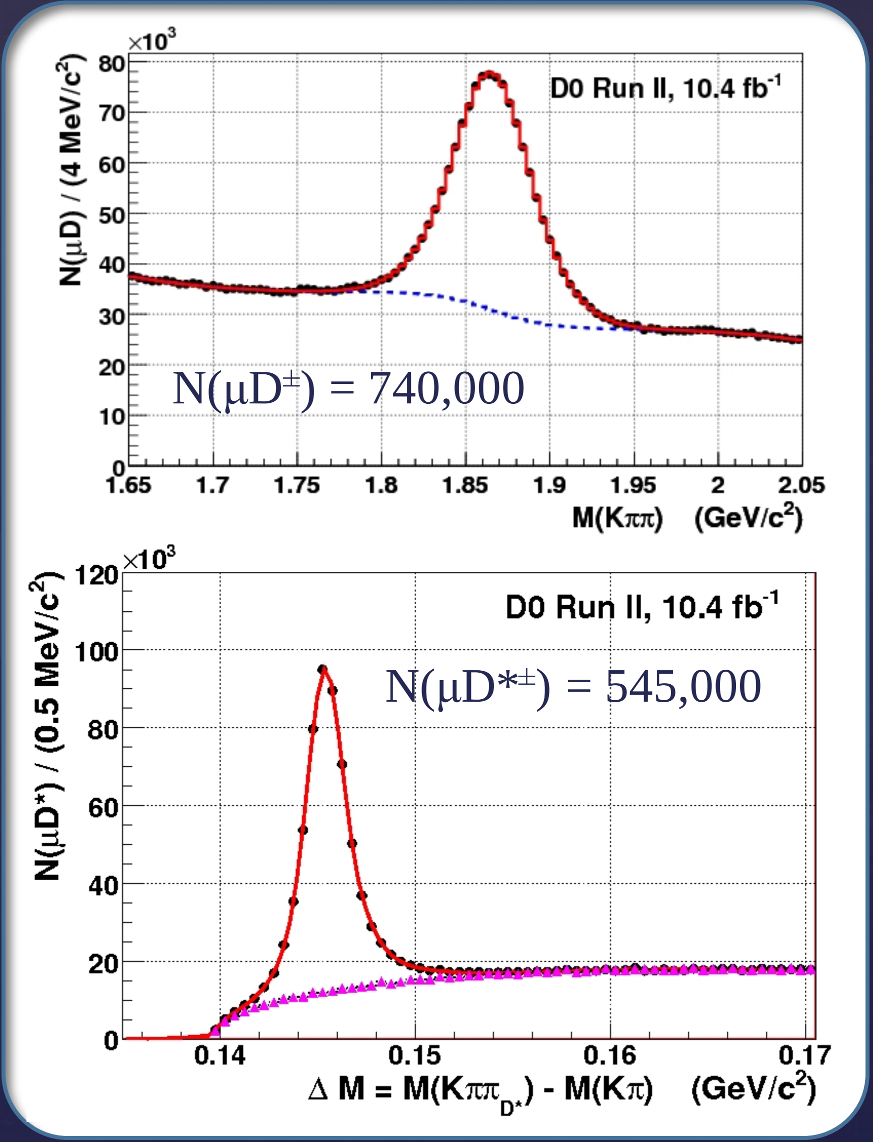
Event Selection

B^0 Channels

Final selections use multivariate discriminants

Final cut on multivariate discriminant chosen to maximize signal significance $S/\sqrt{(S+B)}$

B^0 selection optimized separately in each VPDL bin – significantly increases signal in most useful bins.



Magnet Polarity Weighting

Events are weighted such that sum of weights W is same for four (solenoid, toroid) = (±, ±) polarity configurations.

$$W(\pm,\pm) = N_{\mathrm{min}}/N(\pm,\pm)$$

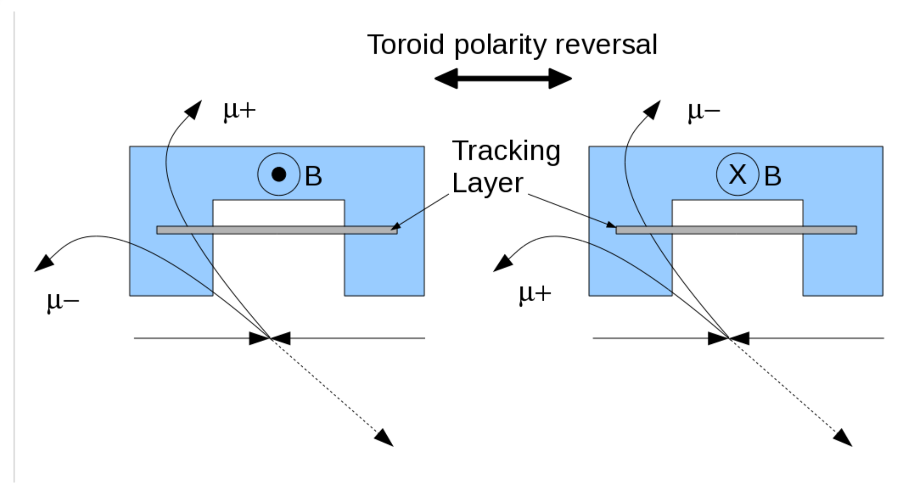
Weights determined separately in each VPDL bin, and for each channel.

Effective statistical loss of around 3-5%

$N(\mu D^{\pm})$: 740,000 → 722,000
(2.4% loss)

$N(\mu D^{*\pm})$: 545,000 → 519,000
(4.8% loss)

$N(\mu D_s^{\pm})$: 216,000 → 203,000
(6.0% loss)



Raw Asymmetry Extraction

$$a_{\mathrm{sl}}^{q} = \frac{A - A_{\mathrm{BG}}}{F^{\mathrm{osc}}_{B^0_{(s)}}}$$

Extracting Raw Asymmetries

$$a_{sl}^{q} = \frac{A - A_{BG}}{F^{osc}_{B^0_{(s)}}}$$

Construct invariant mass distributions that can be fitted to extract $\mu D_{(s)}^{(*)\pm}$ yields:

- **M(φπ)** for $\mu D_s^{\pm}$ channel;
- **M(Kππ)** for $\mu D^{\pm}$ channel;
- **ΔM** = $M(D^0\pi) - M(D^0)$ for $\mu D^{*\pm}$ channel.

Fill charge-specific histograms $H^{\pm}$ for each distribution, and use to construct sum and difference:

$$H_{\text{sum}} = H^+ + H^-$$
$$H_{\text{diff}} = H^+ - H^-$$

Perform simultaneous binned χ^2 fit of sum and difference to extract asymmetry:

$$\chi^2 = \sum_{\text{bin } i=1}^{N} \left[\left(\frac{H^i_{\text{sum}} - F^i_{\text{sum}}}{\sigma^i_{\text{sum}}} \right)^2 + \left(\frac{H^i_{\text{diff}} - F^i_{\text{diff}}}{\sigma^i_{\text{diff}}} \right)^2 \right]$$

$F^i_{\text{sum(diff)}}$ are fit functions $F_{\text{sum(diff)}}$ integrated over width of bin i.

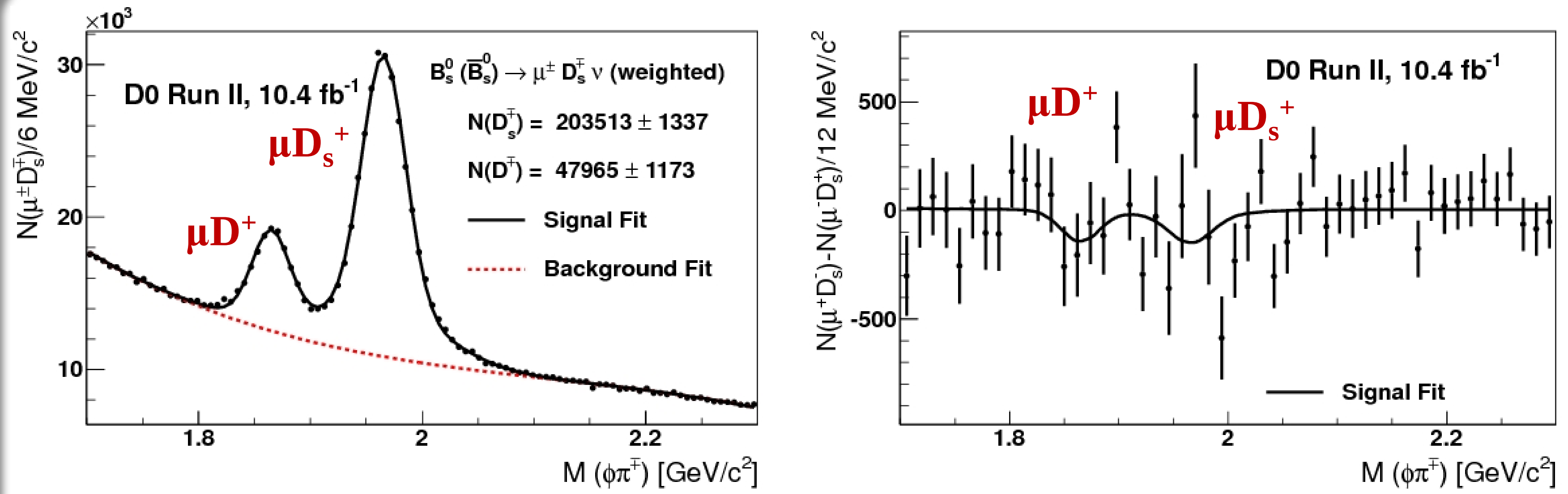
$\sigma^i_{\text{sum}} = \sigma^i_{\text{diff}} = \sqrt{H^i_{\text{sum}}}$

Sum/Difference Fit: $\mu D_s^{\pm}$

$$a_{sl}^{q} = \frac{A - A_{BG}}{F^{osc}_{B^0_{(s)}}}$$

Single time-integrated fit

$A = (-0.40 \pm 0.33)$ %



Smaller peak from $B^0 \rightarrow \mu\nu D^+$

Also measure asymmetry in this component:

$A_{D+} = (-1.21 \pm 1.00)$%

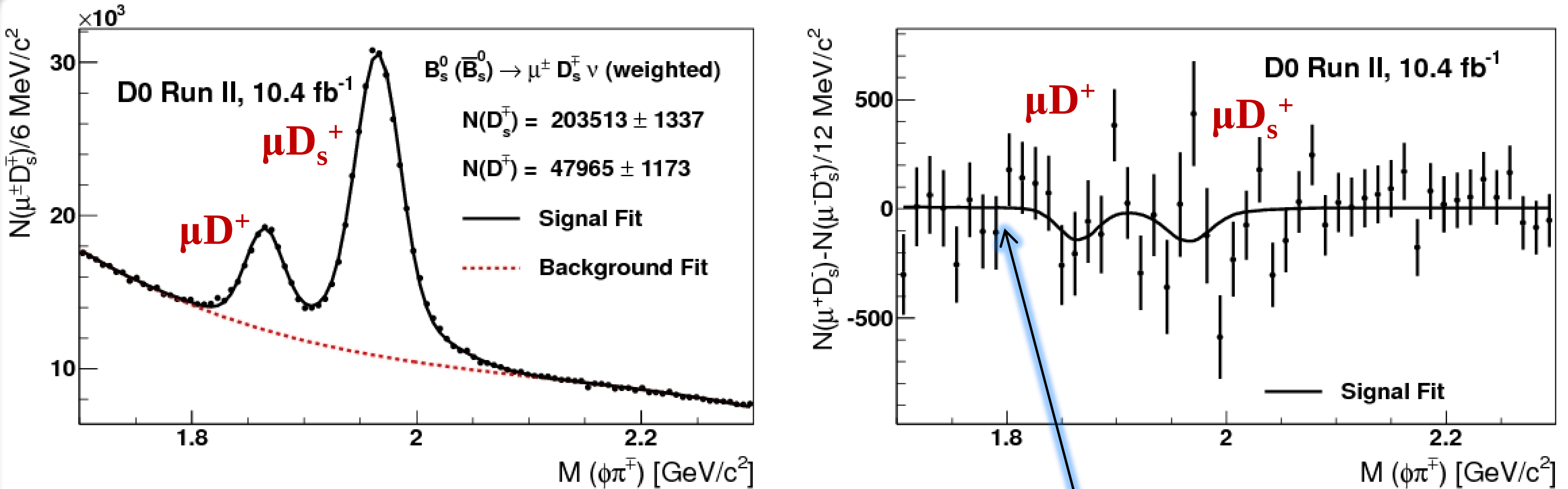
Signal parameters common to both fits – constrained from sum distribution

Sum/Difference Fit: $\mu D_s^{\pm}$

$$a_{sl}^{q} = \frac{A - A_{BG}}{F^{osc}_{B^0_{(s)}}}$$

Single time-integrated fit

A = (−0.40 ± 0.33) %



Smaller peak from $B^0 \to \mu\nu D^+$

Also measure asymmetry in this component:

A_{D+} = (−1.21 ± 1.00)%

Negligible asymmetry in background
A_{BG} = (0.00 ± 0.11)%
Strong indication that track reconstruction asymmetry is small.

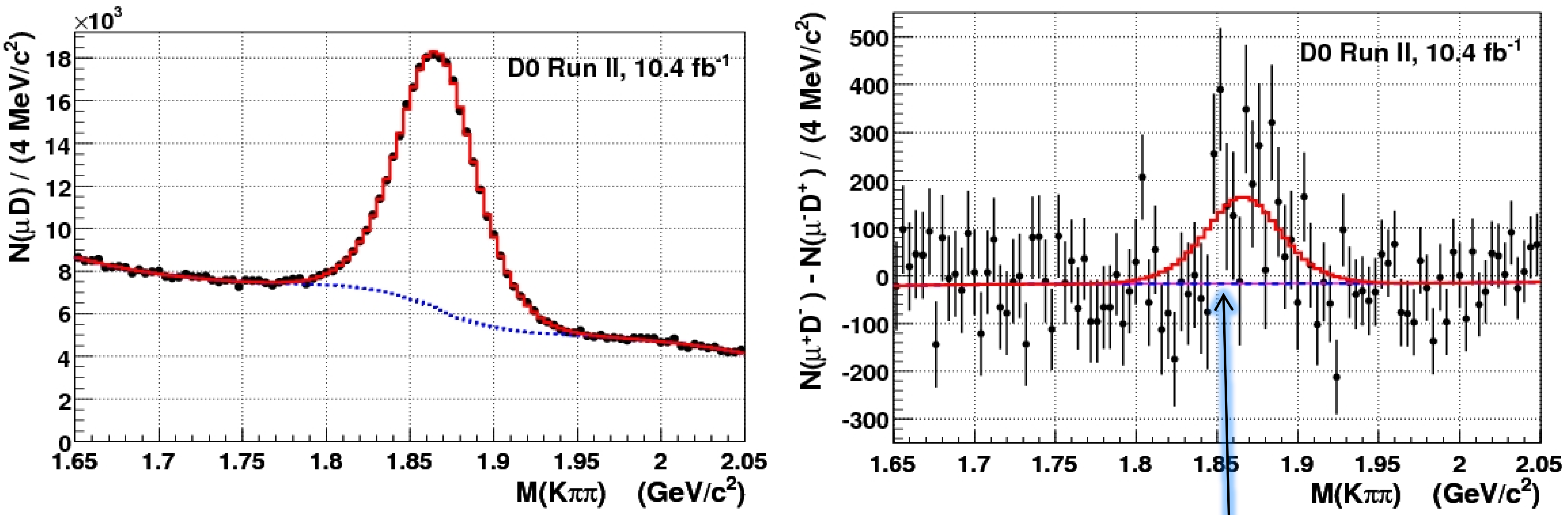
Example Fits: $\mu D^{\pm}$

$$a^q_{\rm sl} = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

For [0.10 < VPDL(B) < 0.20] cm

(Bin with highest a^d_{sl} sensitivity)

A = 1.48 ± 0.41 %



Significant positive asymmetry: expected due to kaon reconstruction effects.

Example Fits: $\mu D^{\pm}$

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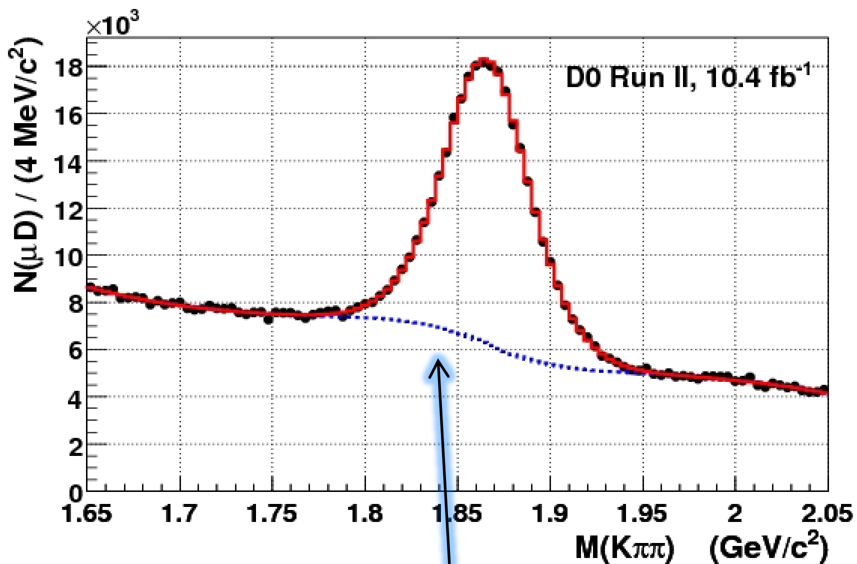
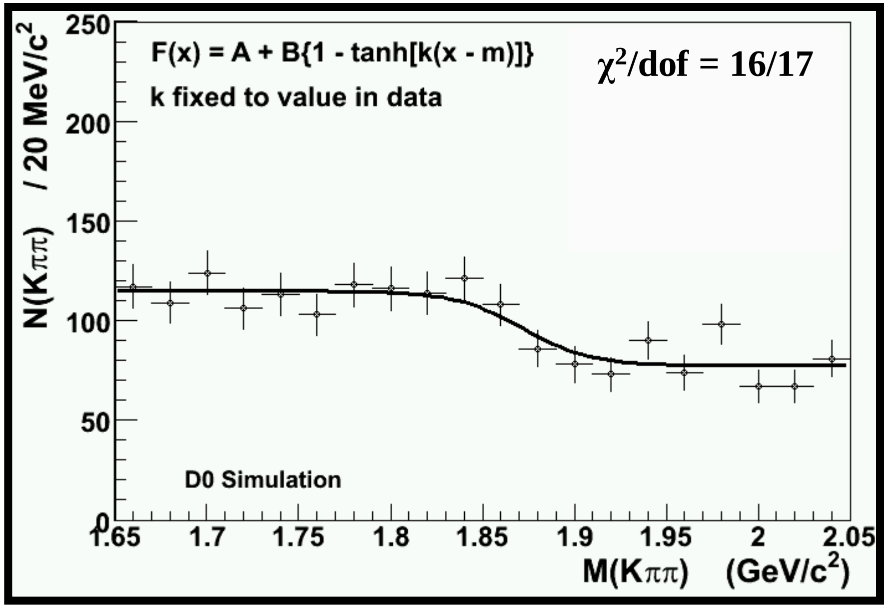




Hyperbolic tangent models effects of partially-reconstructed decays and reflections, e.g.

$D^{-} \rightarrow K^{+}\pi^{-}\pi^{-}\pi^{0}$

$D^{*-} \rightarrow \pi^{-} (D^{0})K^{+}\pi^{-}\pi^{0}$

Individual and collective effects studied and validated using MC simulations

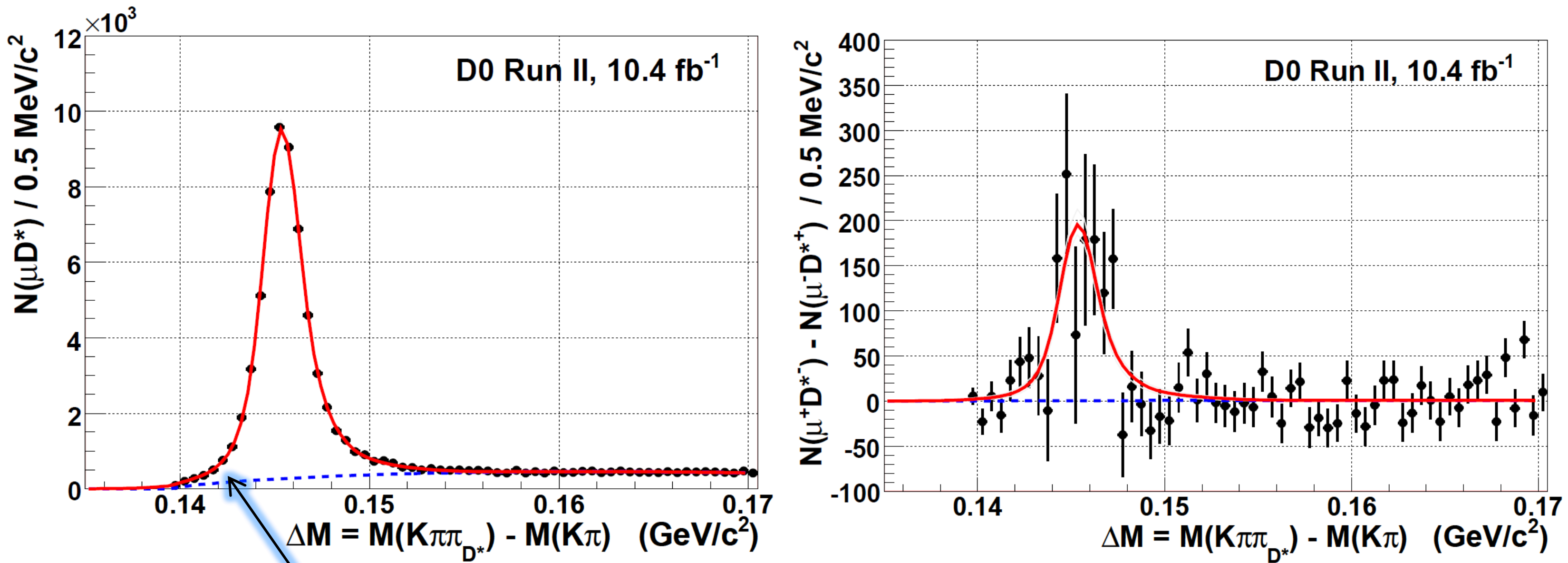
Example Fits: μD*±

$$a^q_{\rm sl} = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

For [0.10 < VPDL(B) < 0.20] cm

(Bin with highest a^d_{sl} sensitivity)

A = 2.11 ± 0.44 %



Proximity of pion threshold skews shapes of signal and background, and necessitates careful study of BG shape.

Validating Fits

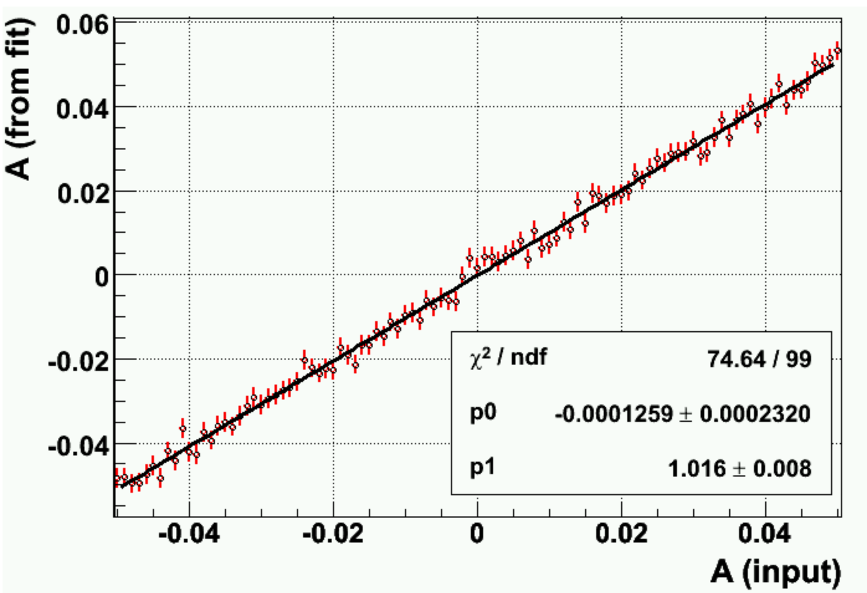
$$a_{\rm sl}^{q} = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

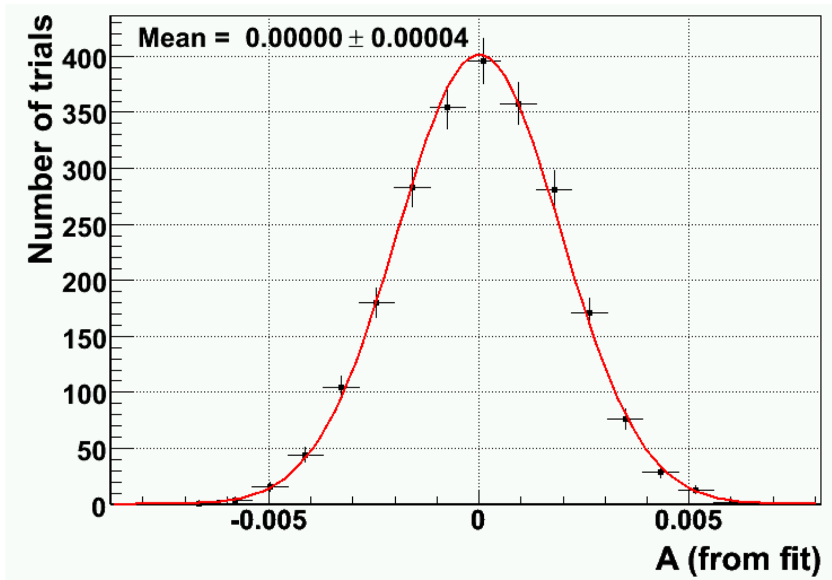
Ensemble tests confirm fits are **unbiased** and report true **uncertainties**:

1) Use random number generator to pick candidate charges by 'flipping a biased coin' to obtain samples with different input asymmetries

2) Perform fit to extract asymmetry

3) Repeat ~5-10K times





Systematic Uncertainties

$$a_{\mathrm{sl}}^{q} = \frac{A - A_{\mathrm{BG}}}{F^{\mathrm{osc}}_{B^0_{(s)}}}$$

Allow simultaneous variations in several aspects of fits:

- Bin widths, upper and lower fitting limits
- Fitting functions (sum/diff for both signal and BG components)
- Alternative weighting scheme

Examine effect on final measured asymmetry over this set of fit variants

$\mu D^{\pm}$ (similar for other channels)

Source	Bin 1 −0.10 – 0.00 cm	Bin 2 0.00 – 0.02 cm	Bin 3 0.02 – 0.05 cm	Bin 4 0.05 – 0.10 cm	Bin 5 0.10 – 0.20 cm	Bin 6 0.20 – 0.60 cm
μD channel						
Bin width	0.09%	0.01%	0.01%	0.01%	0.00%	0.05%
Fit limits	0.17%	0.06%	0.08%	0.05%	0.03%	0.12%
Magnet weighting	0.02%	0.00%	0.00%	0.00%	0.00%	0.01%
Signal model	0.03%	0.03%	0.01%	0.04%	0.01%	0.01%
Background model (sum)	0.03%	0.00%	0.01%	0.01%	0.01%	0.00%
Background model (diff)	0.01%	0.00%	0.01%	0.00%	0.01%	0.02%
Combined systematic	±0.19%	±0.07%	±0.08%	±0.07%	±0.05%	±0.13%
Statistical	±1.28%	±0.35%	±0.32%	±0.33%	±0.41%	±0.88%

For all measurements, systematic uncertainty considerably smaller than statistical.

Detector Asymmetries

$$a_{\rm sl}^{q} = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

Detector Effects – Introduction

Final-state particles can have different detection efficiencies for particles and antiparticles. Two causes:

1) ‘Physics’ asymmetries due to different interaction cross-sections of particles in the detector (matter) material.

Negatively charged **kaons** interact with nucleons to produce hyperons
$\Rightarrow$ shorter path length
$\Rightarrow$ lower reconstruction efficiency
$\Rightarrow$ positive kaon asymmetry

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For B^0 channels ($\mu^+K^+\pi^-\pi^-$): $\mathbf{A_{BG} = a^{\mu} + a^{K} - 2a^{\pi}}$

For B_s^0 channel ($\mu^+\varphi\pi^-$): $\mathbf{A_{BG} = a^{\mu} - a^{\pi}}$

$$a^X \equiv \frac{\varepsilon^{X^+} - \varepsilon^{X^-}}{\varepsilon^{X^+} + \varepsilon^{X^-}}$$

Kaon Reconstruction Asymmetry

Only affects B^0 channels

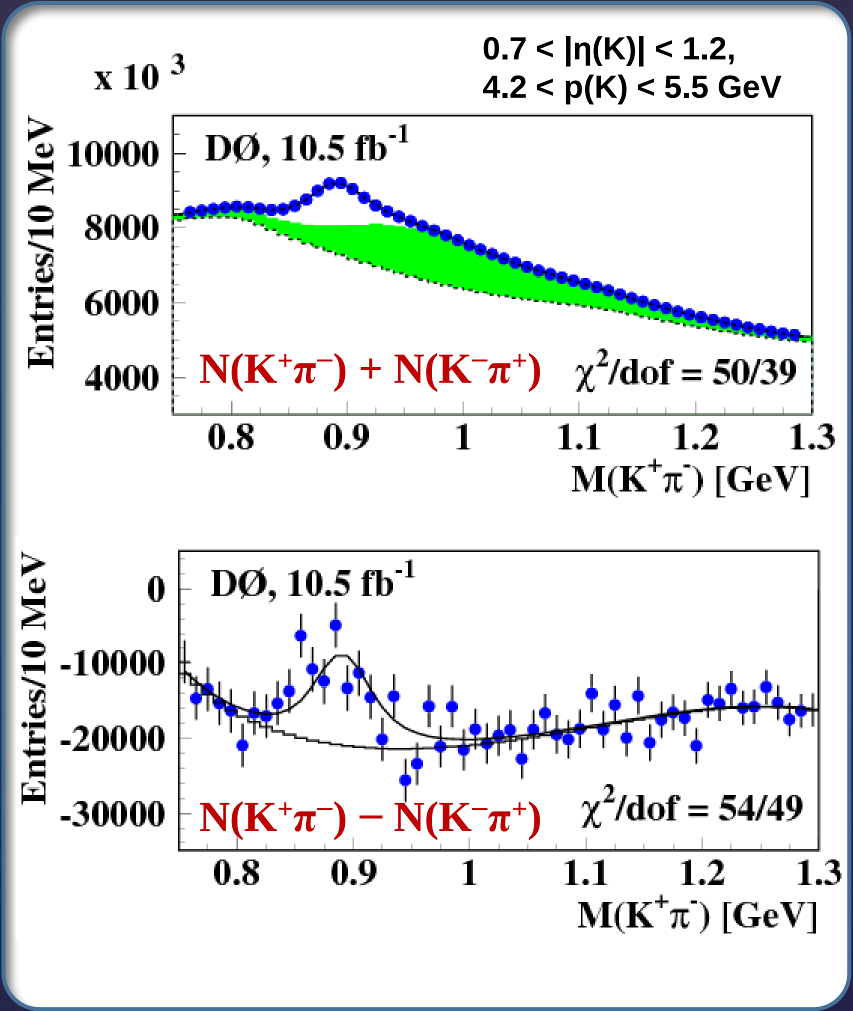
Use dedicated, independent decay channel
$K^{*0} \rightarrow K^+\pi^-$

Dominated by light-quark fragmentation: no underlying source of production/decay asymmetry

Also includes possible **asymmetry** in reconstruction of opposite-charge **pion**:

$$\frac{N(K^+\pi^-) - N(K^-\pi^+)}{N(K^+\pi^-) + N(K^-\pi^+)} = a^K - a^\pi$$

$$A_{BG}(B^0) = a^\mu + a^K - 2a^\pi$$



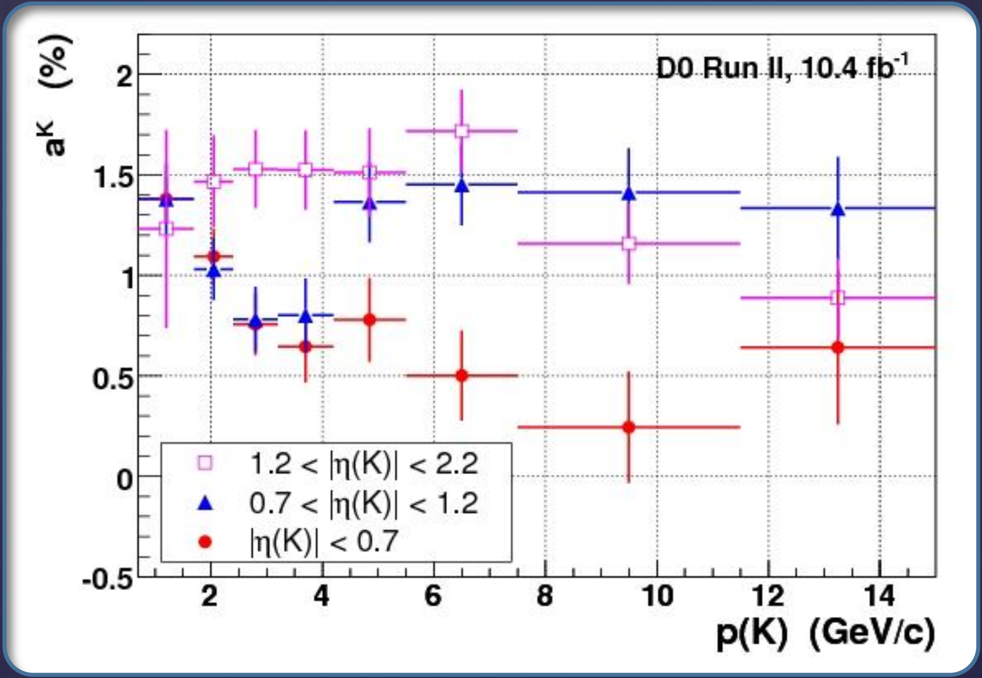
Kaon Reconstruction Asymmetry

Only affects B^0 channels

Use dedicated, independent decay channel **$K^{*0} \rightarrow K^+\pi^-$**

Kaon path-length dependent: perform separately in 24 bins of [p(K),|η(K)|]

Convolute a^K distribution with [p(K),|η(K)|] for each channel and each VPDL bin to obtain final kaon corrections



$$A_{BG}(B^0) = a^\mu + a^K - 2a^\pi$$

Residual Muon Asymmetry

Affects all three channels

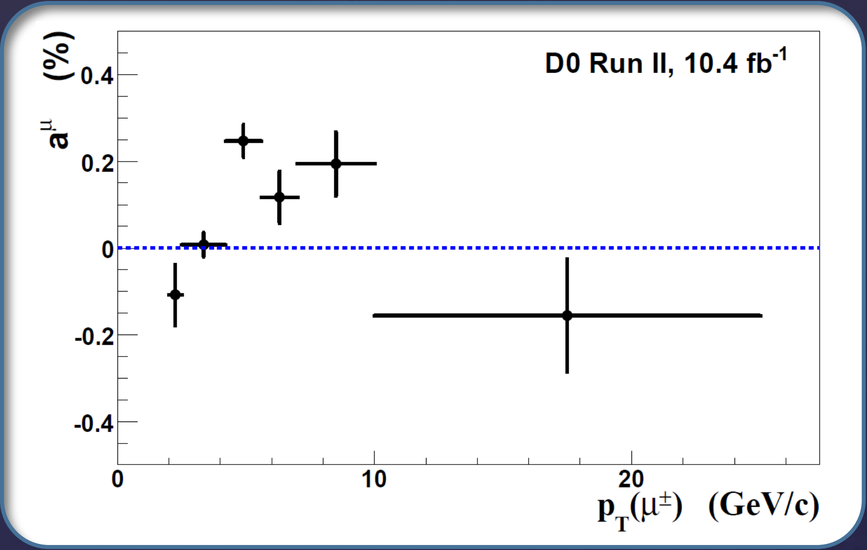
10x smaller than kaon asymmetry.

Asymmetries not perfectly cancelled by magnet polarity reversal

Dedicated channel $\mathbf{J/\psi \rightarrow \mu^+\mu^-}$

Insensitive to track asymmetry – only local muon reconstruction;

Study difference $N(\mu^+ t^-) - N(\mu^- t^+)$ and fit invariant mass distribution to extract asymmetry in $p_T(\mu)$ bins;



$$A_{BG}(B^0) = a^{\mu} + a^{K} - 2a^{\pi}$$

$$A_{BG}(B_s^0) = a^{\mu} - a^{\pi}$$

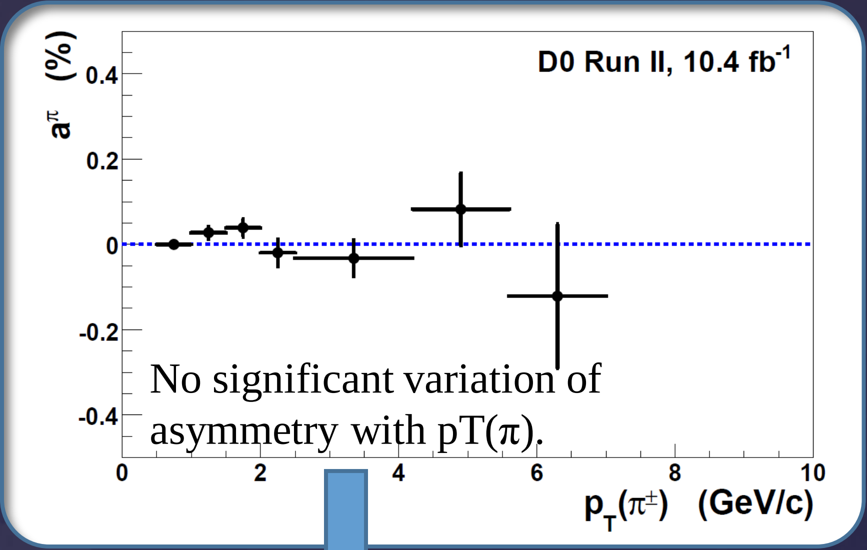
Residual Track Asymmetry

Affects all three channels

Use $\mathbf{K^0_S \rightarrow \pi^+\pi^-}$ decays to test relative track asymmetries versus p_T(track)

Charge-symmetric process: insensitive to absolute charge asymmetry;

Symmetry breaks down when dividing into separate pT samples.



1) Overall track asymmetry will cancel in signal final states ($\mu^+\pi^-$)

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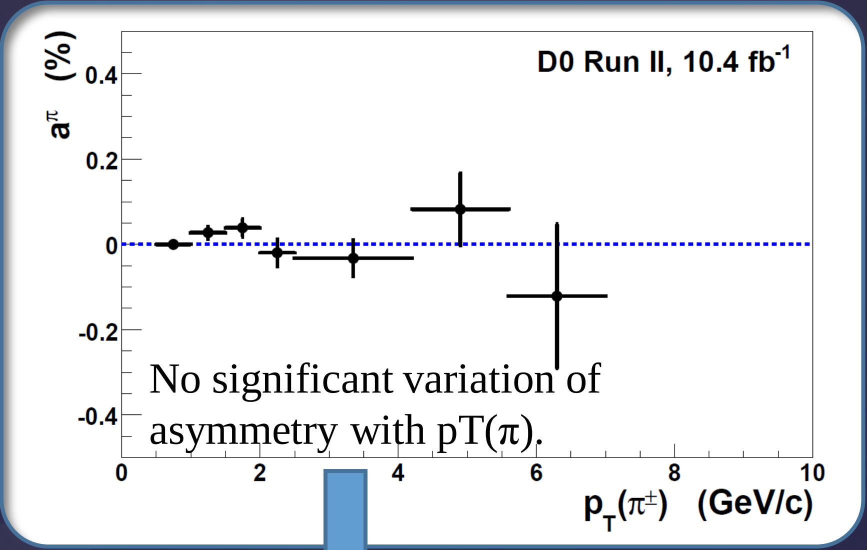
Symmetry breaks down when dividing into separate pT samples.

Additional dedicated channel ($K^{*\pm} \rightarrow K_S{}^0\pi^\pm$) finds no evidence for an absolute asymmetry.

Assign $a^\pi = (0.00 \pm 0.05)\%$



1) Overall track asymmetry will cancel in signal final states ($\mu^+\pi^-$)

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Final A_{BG} Corrections

- Kaon asymmetry x10 larger than muon asymmetry
- Asymmetries consistent across VPDL bins
- Small differences between channels due to different kinematics

For B_s^0 channel:

A_{BG} = (0.11 ± 0.06)%

For $B^0 \to \mu D^{\pm}$ channel, A_{BG} = 1.23%→1.27% ± 0.07%

	Bin 1 −0.10 – 0.00 cm	Bin 2 0.00 – 0.02 cm	Bin 3 0.02 – 0.05 cm	Bin 4 0.05 – 0.10 cm	Bin 5 0.10 – 0.20 cm	Bin 6 0.20 – 0.60 cm
μD channel						
A (%)	2.70 ± 1.28 ± 0.19	1.02 ± 0.35 ± 0.07	1.16 ± 0.32 ± 0.08	1.50 ± 0.33 ± 0.07	1.48 ± 0.41 ± 0.05	1.20 ± 0.88 ± 0.13
a^K (%)	1.128 ± 0.041 ± 0.014	1.124 ± 0.040 ± 0.014	1.141 ± 0.040 ± 0.014	1.147 ± 0.040 ± 0.014	1.157 ± 0.040 ± 0.015	1.157 ± 0.040 ± 0.014
a^μ (%)	0.102 ± 0.025 ± 0.008	0.105 ± 0.027 ± 0.009	0.107 ± 0.029 ± 0.012	0.107 ± 0.029 ± 0.013	0.108 ± 0.028 ± 0.011	0.108 ± 0.028 ± 0.009
A_{BG} (%)	1.230 ± 0.048 ± 0.053	1.229 ± 0.048 ± 0.053	1.248 ± 0.049 ± 0.053	1.254 ± 0.049 ± 0.054	1.265 ± 0.049 ± 0.053	1.265 ± 0.049 ± 0.053

(For $B^0 \to \mu D^{*\pm}$ channel, A_{BG} = 1.18%→1.20% ± 0.08%)

Oscillated $B_{(s)}^0$ Fraction

$$a_{\rm sl}^q = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

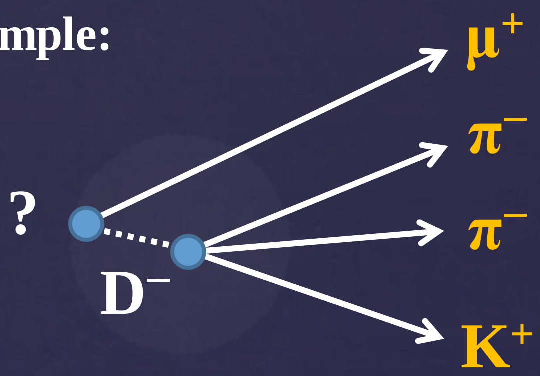
Dilution from non-mixed B mesons

Semi-inclusive event selection: missing neutrino prevents unique identification of $B_{(s)}^0$ mesons;

Some $\mu D_{(s)}^{(*)}$ candidates arise from other sources:

- Prompt $c \rightarrow D$
- B^+ decays
- B^0 in B_s^0 channel / B_s^0 in B^0 channel
- b baryons (negligible)

Example:



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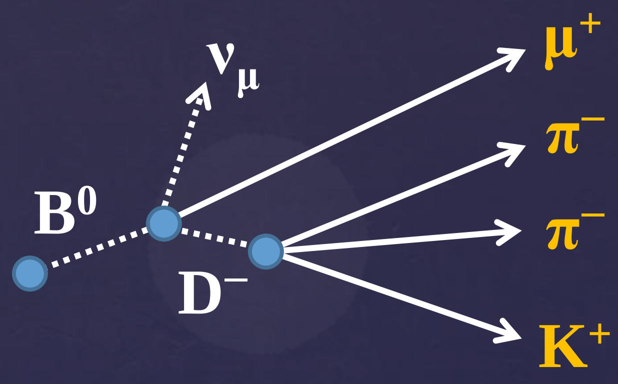

$Br(B^0 \to \mu^+ \nu D^-) = \mathbf{2.18 \pm 0.12\ \%}$

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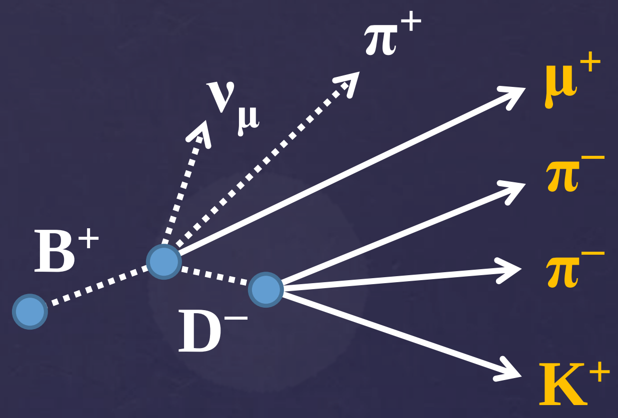

$Br(B^0 \to \mu^+ \nu D^-) = 2.18 \pm 0.12$ %

$Br(B^+ \to \mu^+ \nu \pi^+ D^-) = 0.42 \pm 0.05$ %

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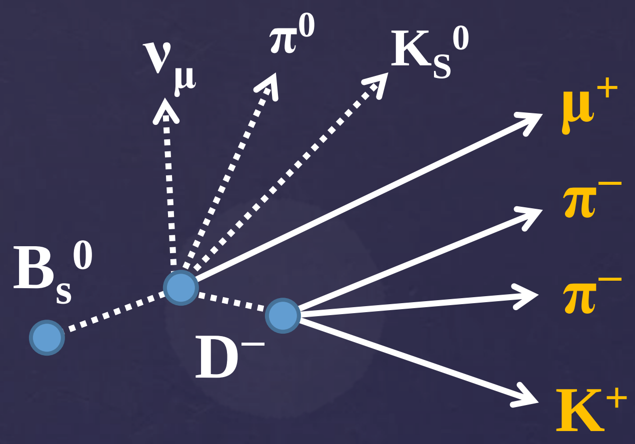

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$\mathrm{Br}(B_s^0 \rightarrow \mu^+ \nu D_{s1}^- \rightarrow \mu^+ \nu \pi^0 K_S^0 D^-) = 0.08 \pm 0.02\ \%$

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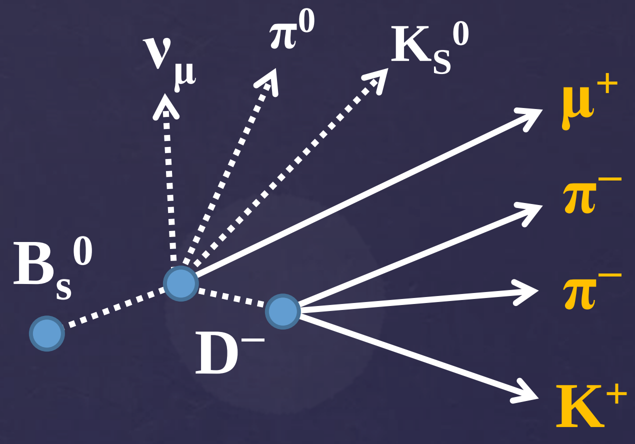

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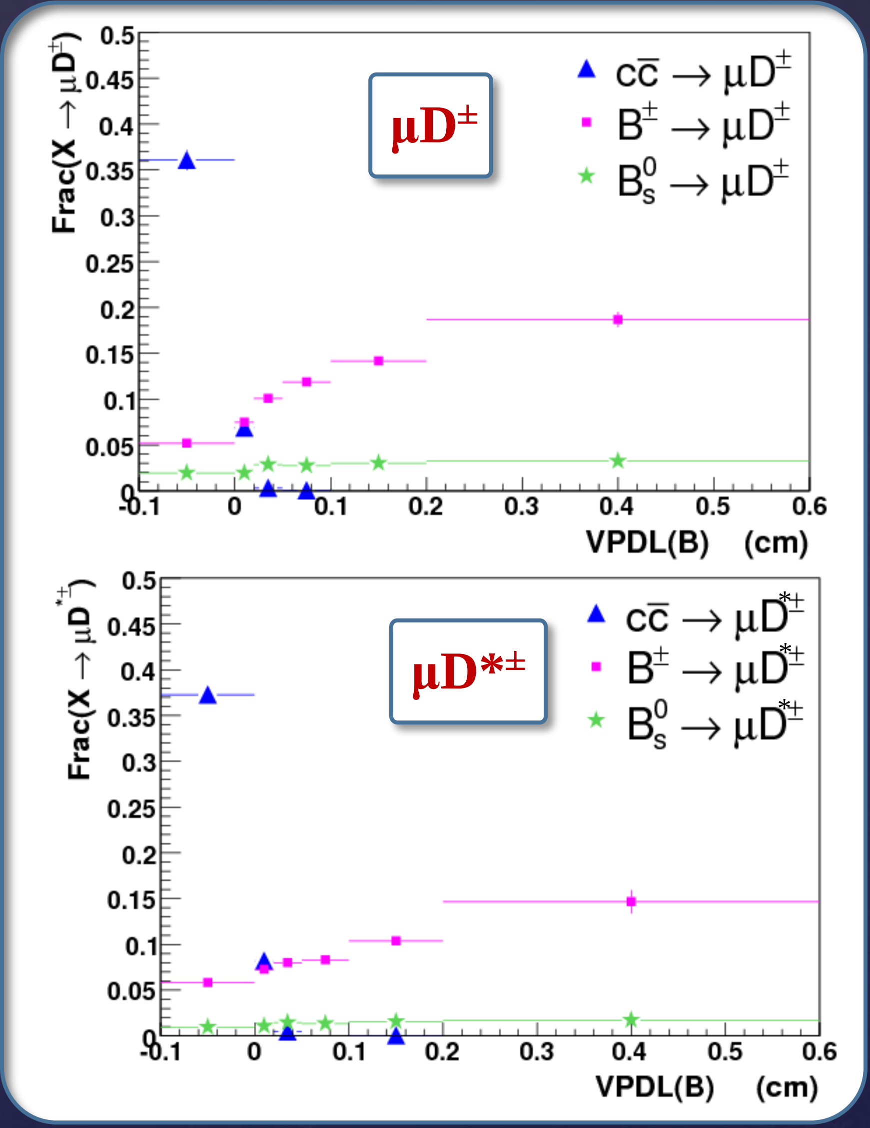
$\Rightarrow$ expect ~15% of μ^+D^- events to come from $B^\pm$, <3% from B_s^0.

Dilution from non-mixed B mesons

Inclusive Monte Carlo simulation of
$X \rightarrow \mu D_{(s)}^{(*)}$
(dedicated sample for each channel)

- Prompt c → D
  - Only in first 2 VPDL bins (control region)
- B^+ decays
  - Increasing contribution versus VPDL (longer-lived than B^0)
- B_s^0 in B^0 channel
  - Small and steady contribution



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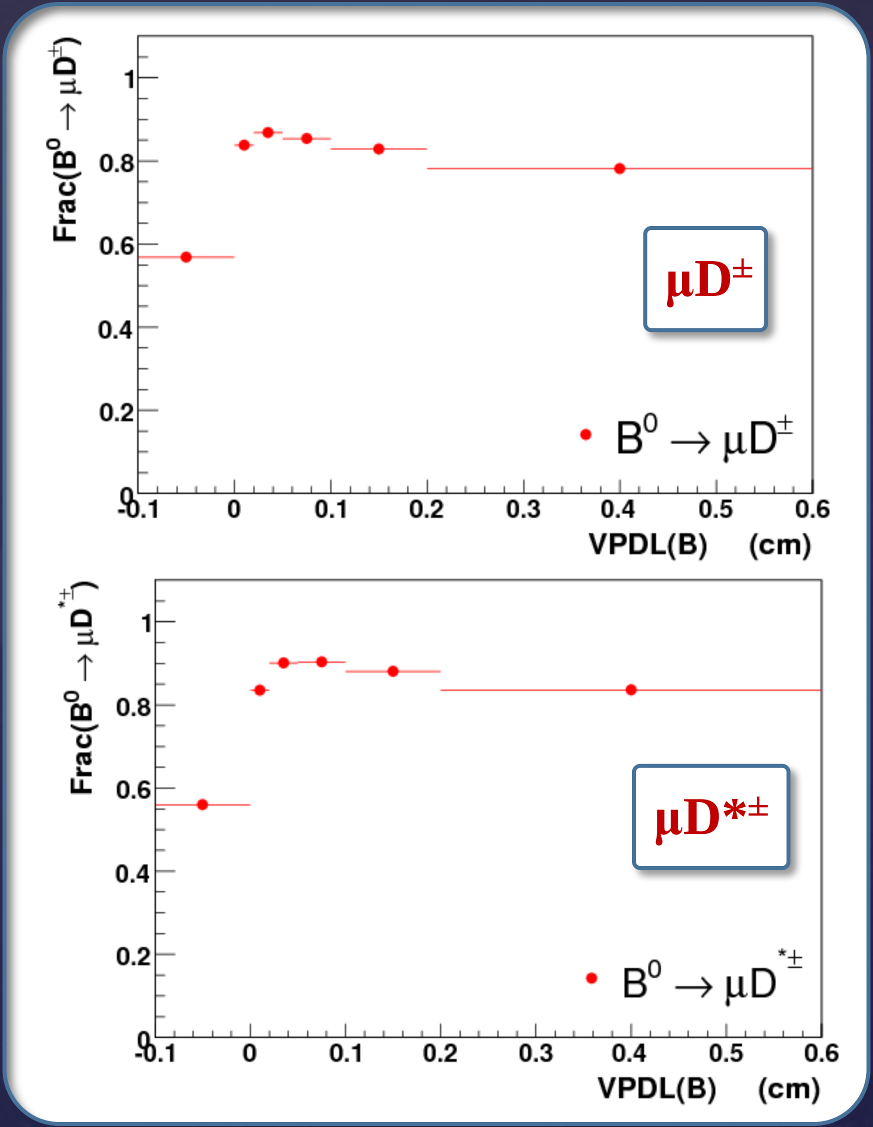
>80% of $\mu D^{(*)}$ signal candidates are from B^0 decays



Dilution from non-mixed B mesons

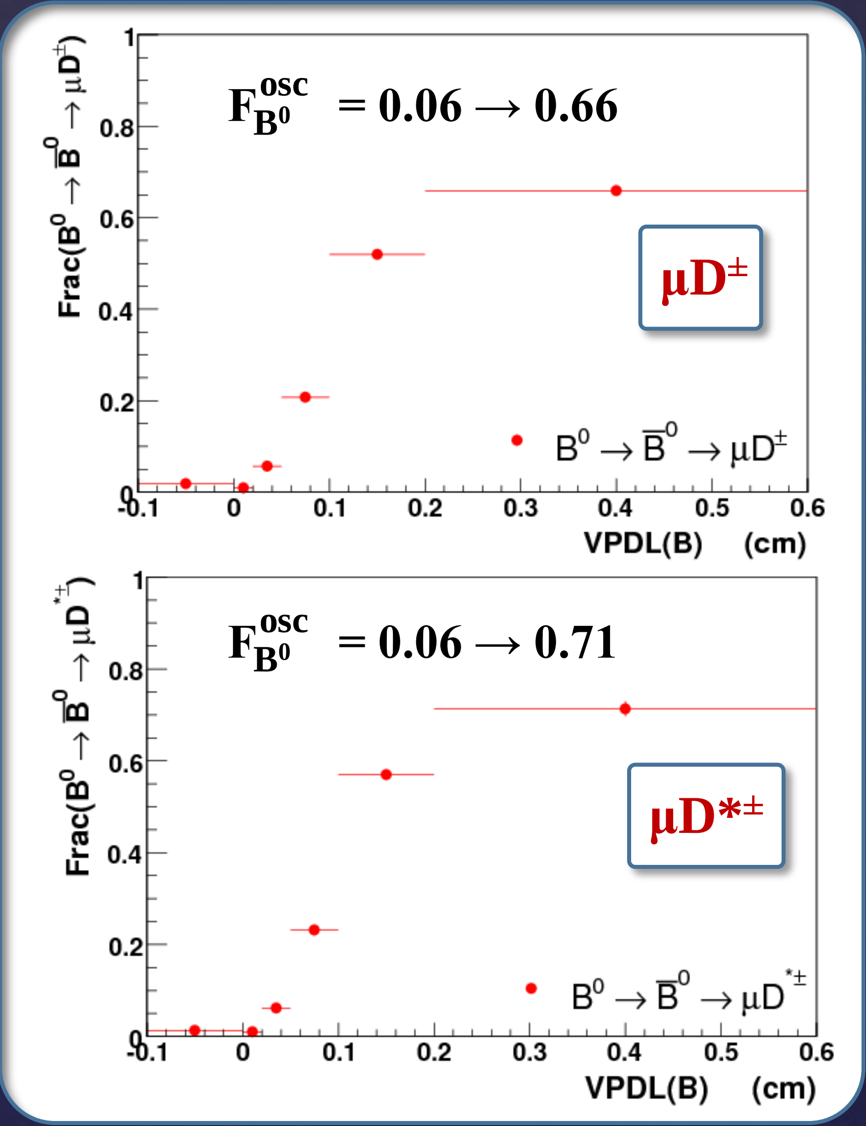
Simulate oscillations by weighting MC events according to their proper decay time:

$$P_i(B^0) = \frac{1}{2}[1 - \cos(\Delta M_d \cdot t_i)]$$

For B_s^0 channel also include (tiny) effect of nonzero $\Delta\Gamma_s$:

$$F^{osc}_{B_s^0} = 0.465 \pm 0.017$$

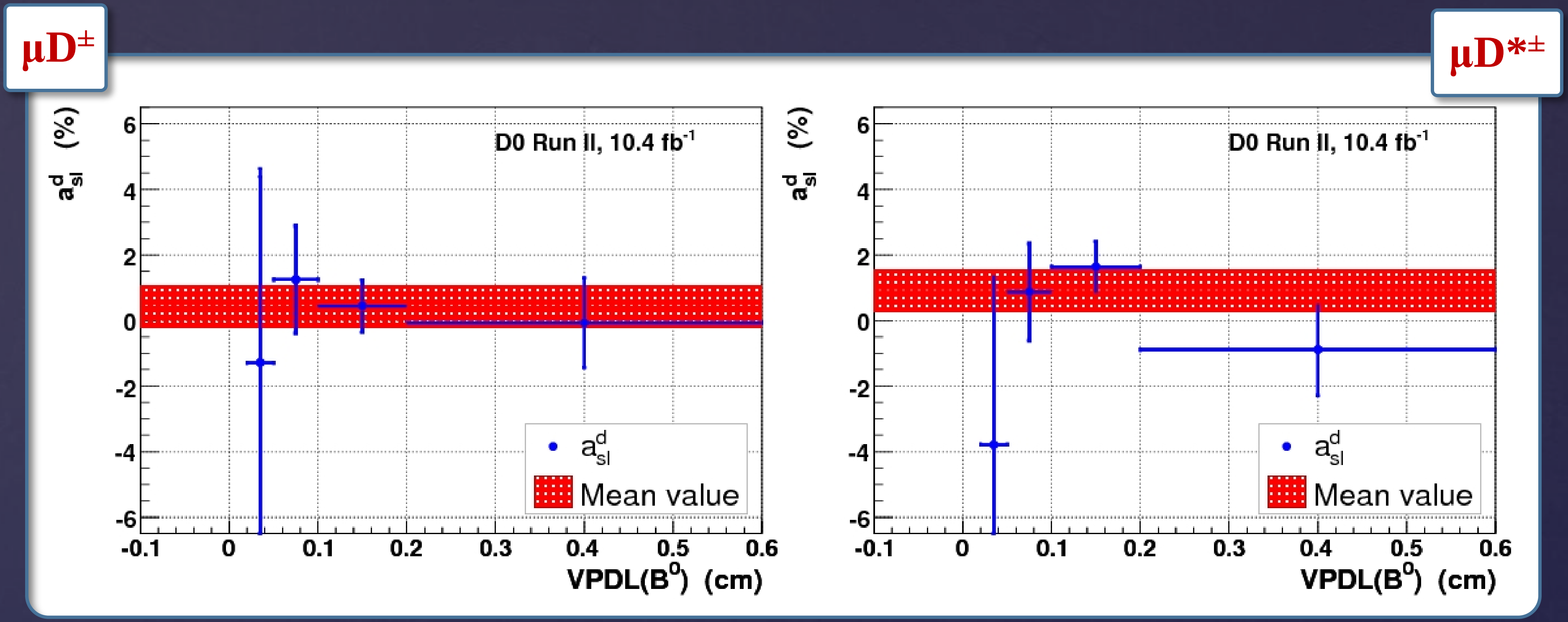
Assign systematic uncertainties for limited knowledge of lifetimes, Δm_q, and decay branching ratios.



Final Results & Combination

$$a_{\rm sl}^{q} = \frac{A - A_{\rm BG}}{F^{\rm osc}_{B^0_{(s)}}}$$

B^0 mesons: a^d_{sl} versus VPDL



Combine within each channel taking all correlations into account (via pseudo-experiment ensembles):

$$a^d_{\rm sl}(\mu D) = [0.43 \pm 0.63\ (\text{stat.}) \pm 0.16\ (\text{syst.})]\%$$
$$a^d_{\rm sl}(\mu D^*) = [0.92 \pm 0.62\ (\text{stat.}) \pm 0.16\ (\text{syst.})]\%$$

Combination and B_s^0 Results

Combine two $\mathbf{a^d_{sl}}$ measurements, with correlations accounted for:

World's best!

$$a^d_{\mathrm{sl}} \;=\; [0.68 \pm 0.45\;(\mathrm{stat.}) \pm 0.14\;(\mathrm{syst.})]\%$$

- Consistent with SM prediction
- More precise than existing WA from B-factories: $(-0.05 \pm 0.56)\%$

Corresponding time-integrated measurement of $\mathbf{a^s_{sl}}$:

World's best! *

$$a^s_{\mathrm{sl}} = [-1.08 \pm 0.72\,(\mathrm{stat}) \pm 0.17\,(\mathrm{syst})]\,\%$$

(* : for a few weeks…)

- Supersedes previous worlds-best measurement (D0, 2009)
- Consistent with results of dimuon asymmetry, and with SM.
- LHCb (preliminary): $a^s_{sl} = (-0.24 \pm 0.54 \pm 0.33)\%$

a^d_{sl} Dependence on VPDL

$F^{osc}_{B^0}$ is strong function of VPDL

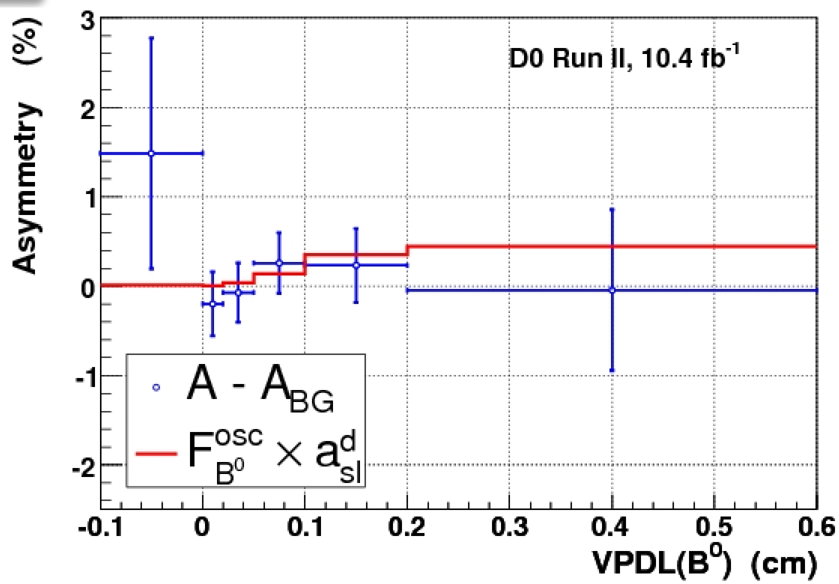
$\Rightarrow$ Any real physical asymmetry from B^0 mixing should be VPDL dependent;

Plot $(A - A_{BG})$ versus VPDL, to look for dependence:

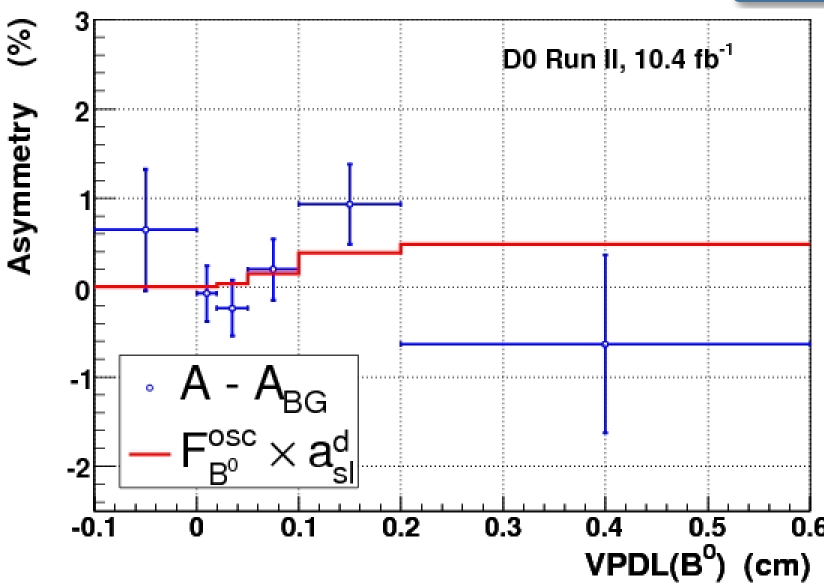
$\chi^2 = 2.3$ (4.5) for a^d_{sl} from this measurement;

2.7 (6.9) for SM value of a^d_{sl} (≈ 0)

μD±



μD*±



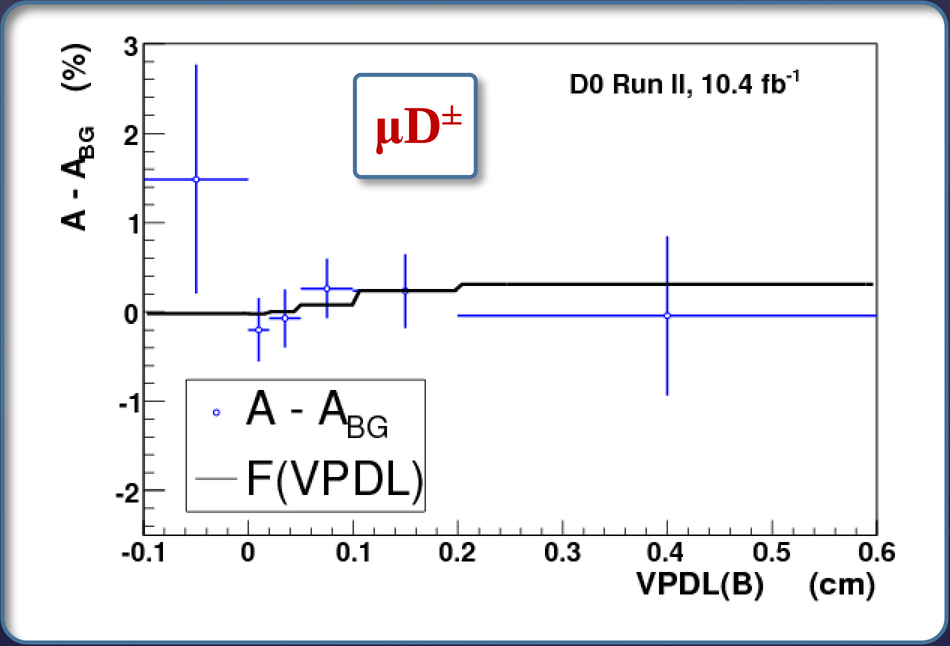
a^d_{sl} Dependence on VPDL

Now **fit** observed asymmetry ($A - A_{BG}$) to expected VPDL dependence:

$$F(\text{VPDL}) = A_{\text{const}} + F^{\text{osc}}_{B^0}(\text{VPDL}) \cdot a^d_{\text{sl}}$$

Constant term: accounts for any possible residual asymmetries not considered.

a^d_{sl}: free parameter – depends only on VPDL ***shape*** of ($A - A_{BG}$).



From fit:

a^d_{sl} = **(0.51 ± 0.86) %**

compare ***(0.43 ± 0.65) %*** *from nominal method*

A_{const} = **(−0.03 ± 0.23) %**

i.e. any residual asymmetries are small and insignificant.

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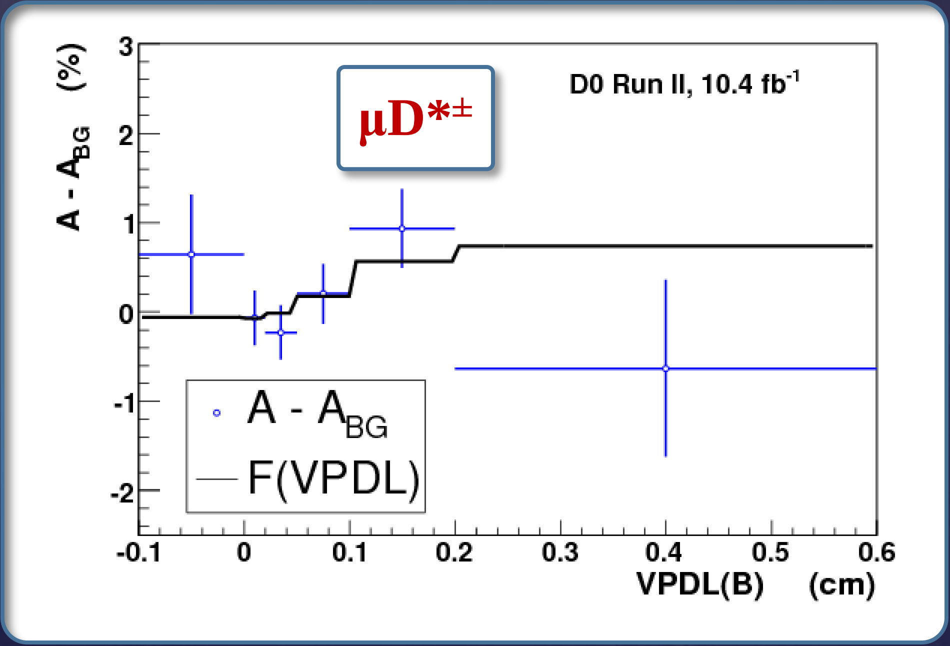


From fit:

a^d_{sl} = **(1.25 ± 0.87) %**

*compare **(0.92 ± 0.65) %** from nominal method*

A_{const} = **(−0.09 ± 0.21) %**

i.e. any residual asymmetries are small and insignificant.

Cross-Checks

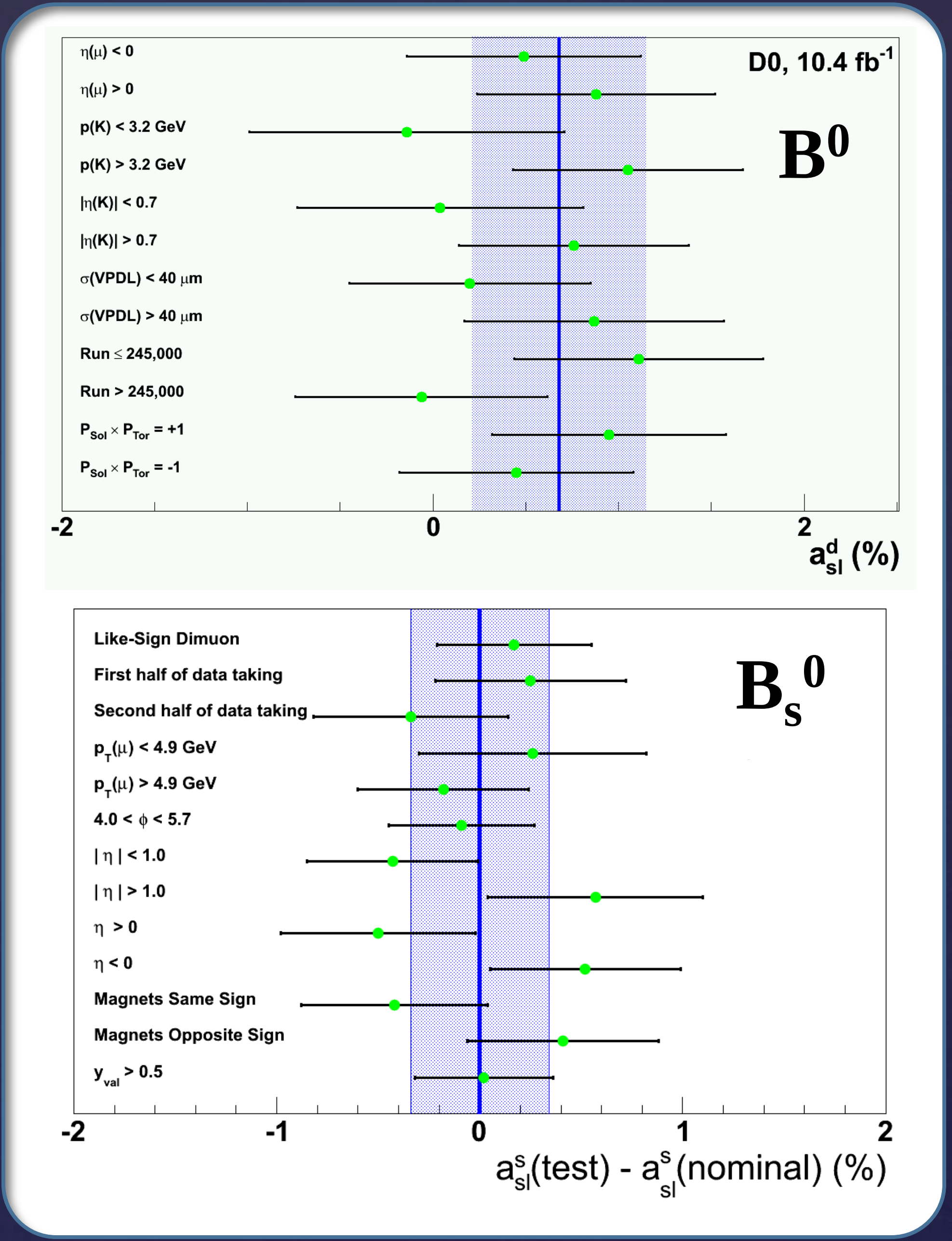
Repeat entire analyses using pairs of orthogonal sub-sets of data, to test stability of results

Split according to:

- Forward/backward
- Forward/central
- Low/high momentum
- early/late runs

Plus repeat with different muon selection, limited φ range …

All measurements consistent with each other and central value



Combination

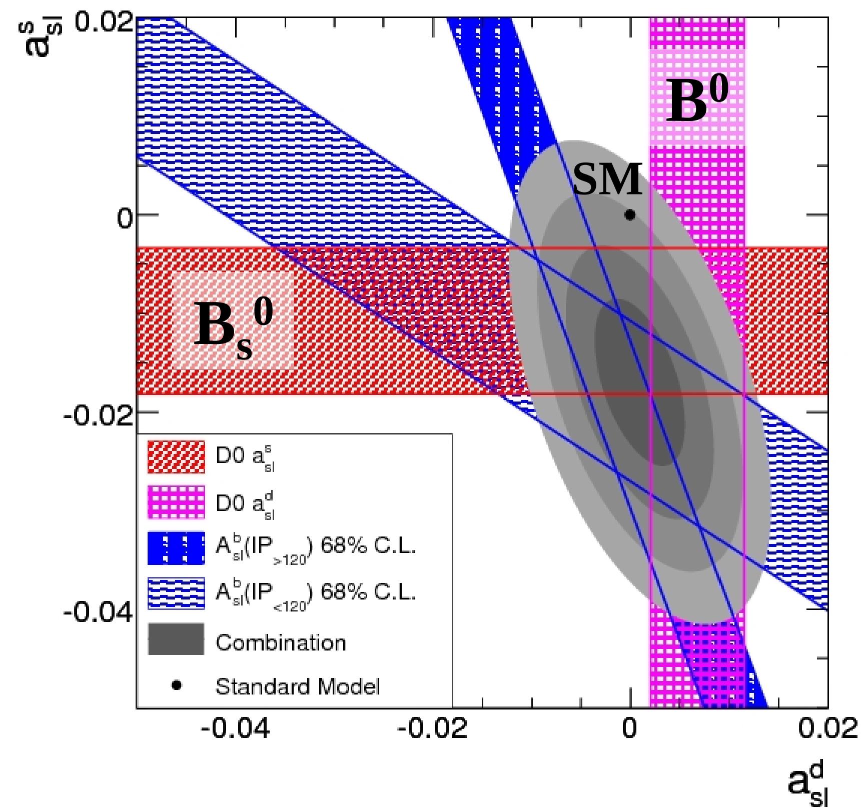
Combine D0 results from dimuon asymmetry (2011), a^d_{sl} and a^s_{sl}:

$$a^d_{\rm sl}(\text{comb.}) = (0.10 \pm 0.30)\%,$$
$$a^s_{\rm sl}(\text{comb.}) = (-1.70 \pm 0.56)\%$$

Correlation coefficient: −0.50

χ^2/dof = **2.9/2**

p-value of SM: **0.36% (2.9σ)**



B^0 meson: consistent with SM (zero)

B_s^0 meson: **>3σ evidence** for anomalous CPV, driven by dimuon asymmetry measurements

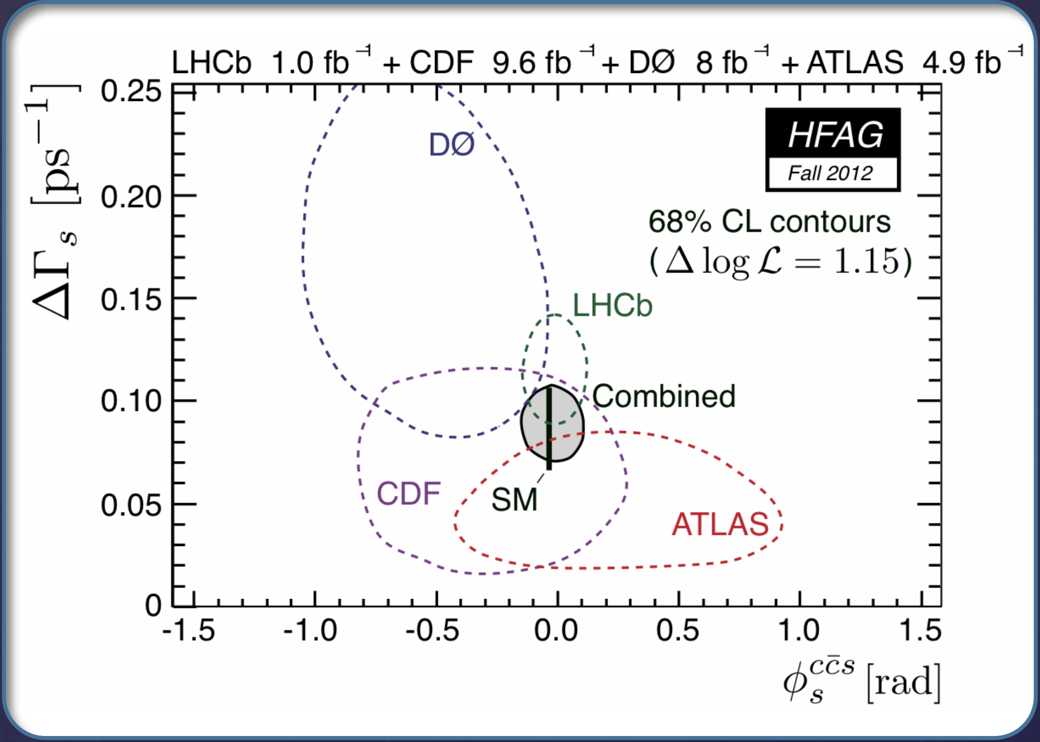
What about $B_s^0 \to J/\psi\varphi$?

Measurements of CP violating phase in $B_s^0 \to J/\psi\varphi$ channel all consistent with SM prediction
(D0, CDF, LHCb, Atlas)

This is a test of CPV in the *interference between mixing and decay*

New Physics contributions to this channel *expected* to be similar to those in mixing alone, but still places for CPV to hide.

Need further study of CP violating parameters from as many angles as possible.



Summary

- We present new precise measurements of the semileptonic mixing asymmetry in B^0 and B_s^0 mesons:

$$a_{sl}^{d} = [0.68 \pm 0.45\ (\text{stat.}) \pm 0.14\ (\text{syst.})]\%$$

$$a_{sl}^{s} = [-1.08 \pm 0.72\,(\text{stat}) \pm 0.17\,(\text{syst})]\,\%$$

- When combined with dimuon asymmetry result, **3σ evidence of anomalously large CPV in B_s^0 mixing**
- Data-driven methods, using strengths of D0 detector
- Limited input from MC
- Many cross-checks validate measurements

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B_s^0 arXiv:1207.1769 [hep-ex]
Submitted to PRL

B^0 arXiv:1208.5813 [hep-ex]
Accepted by PRD

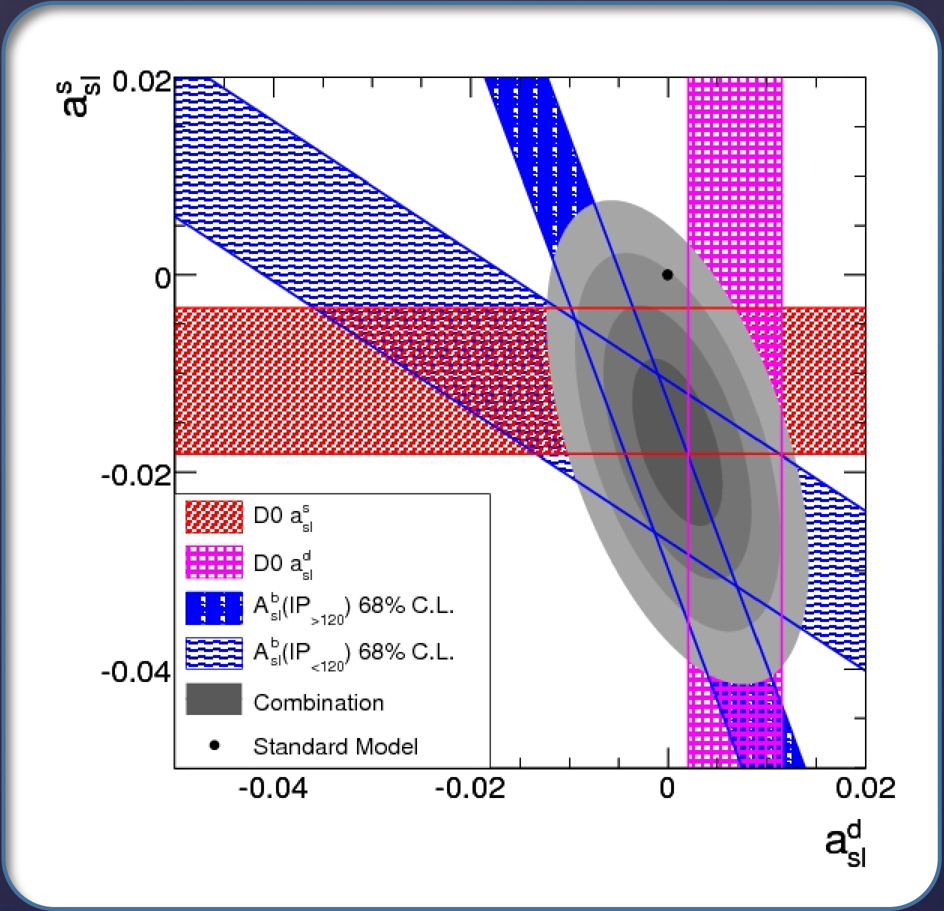
Outlook

New measurements consistent with dimuon asymmetry *and* with SM predictions

Insufficient to resolve tension, but suggestive of CPV in B_s^0 mixing

Need further investigation of semileptonic mixing asymmetries, plus constraints on direct CPV in B and D mesons

Working on updated dimuon asymmetry analysis from D0, with several improvements and extensions



Thanks for listening

Extra Slides

Additional combination

Combination (including B-fac a^d_{sl})

Combine D0 results from dimuon asymmetry (2011), a^d_{sl} and a^s_{sl}:, and existing WA of a^d_{sl} from B-factories.

$$a^d_{\mathrm{sl}}(\mathrm{comb.}) = (0.07 \pm 0.27)\%,$$
$$a^s_{\mathrm{sl}}(\mathrm{comb.}) = (-1.67 \pm 0.54)\%$$

Correlation coefficient: −0.46

χ^2/dof = **2.0/2**

p-value of SM: **0.37%**

a^s_{sl}(LHCb) also shown for comparison

$(-0.24 \pm 0.63)\%$